UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AFOSR-TR-95

0794

REPORT DOCUMENTATION PAGE

DTIC ELECTE JAN 0 5 1996 S F D

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS None
2a. SECURITY CLASSIFICATION AUTHORITY N/A	3. DISTRIBUTION/AVAILABILITY OF REPORT Distribution unlimited Approved for public release
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UTK-PSL 95-4	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION UTK Plasma Science Laboratory 6b. OFFICE SYMBOL (If applicable) ECE Dept.	7a. NAME OF MONITORING ORGANIZATION AFOSR/NE (Dr. Robert J. Baker)
6c. ADDRESS (City, State, and ZIP Code) Room 409, Ferris Hall Department of Elect. & Comp. Engr. University of Tennessee Knoxville, TN 37996-2100	7b. ADDRESS (City, State, and ZIP Code) Building 410, Room B115 Bolling Air Force Base 110 Duncan Ave. Code NE Washington, DC 20332-001
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR 8b. OFFICE SYMBOL (If applicable) NE	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR F49620-94-10249
8c. ADDRESS (City, State, and ZIP Code) Bldg. 410, Room B115; 110 duncan Ave. Code NE Bolling Air Force Base Washington, DC 20332-0001	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 61102F PROJECT NO.: 2301 TASK NO.: ES WORK UNIT ACCESSION NO.:

11. TITLE (Include Security Classification)

"Investigation of A Uniform Glow Discharge Plasma In Atmospheric Air" - UNCLASSIFIED

12. PERSONAL AUTHOR(S)

J. Reece Roth, Principal Investigator

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Scientific	FROM 4/1/94 TO 3/31/95	1995, June 26	

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	physics, plasma, RF-plasma interactions, plasma cloaking, glow discharge, atmospheric glow discharge, drag reduction, boundary layer control
20	.09		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

During this year, we demonstrated the ability not only to cover the surface of a simulated aircraft fuselage with a thin layer of plasma at one atmosphere in both atmospheric air and helium, but we also demonstrated that this plasma layer would not blow away under the impact of a jet of air from the laboratory service air supply.

These results strongly suggest that the one atmosphere plasma layer might be useful for boundary layer control and drag reduction on aircraft. This contract has also resulted in 3 issued patents (to which the U.S. Government has a royalty-free license); two patent disclosures; two poster paper presentations at conferences, two archival journal pulications, and two invited seminar presentations, at the Kirtland AFB and at the NASA-Langley Research Center. It is expected that this work will continue in the wind tunnels at Langle

DTIC QUALITY INSPECTED 2

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED-Distribution Unlimited
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Robert J. Barker	22b. TELEPHONE (Include Area Code) (202) 767-5011 22c. OFFICE SYMBOL AFOSR/NE

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Report PSL 95-4

Final Scientific Report

INVESTIGATION OF A UNIFORM GLOW DISCHARGE PLASMA IN ATMOSPHERIC AIR

Submitted to

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

by

Prof. J. Reece Roth, Principal Investigator
UTK Plasma Science Laboratory
Department of Electrical & Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

for

Dr. Robert J. Barker
NE Program Manager
Air Force Office of Scientific Research
110 Duncan Ave, Room B115
Bolling Air Force Base
Washington, D.C. 20332-0001

UTK Plasma Science Laboratory
Report No. PSL 95-5
Submitted June 26, 1995

Period Covered: April 1, 1994 to March 31, 1995

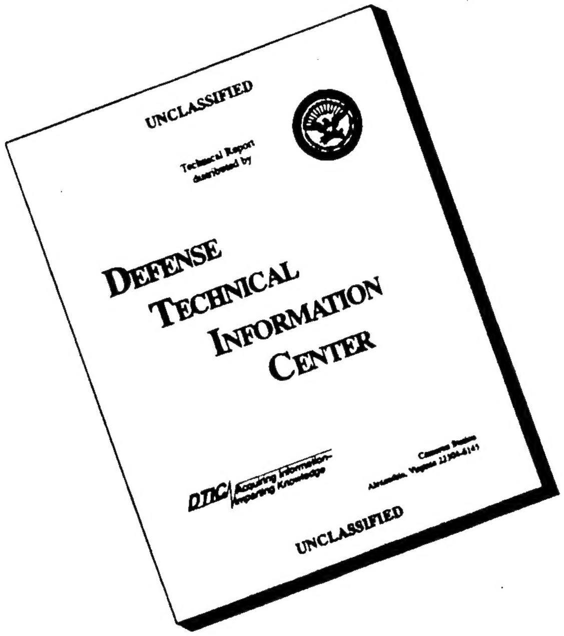
PRINCIPAL INVESTIGATOR: J. Reece Roth
Phone: (615) 974-4446 (Office)
FAX: 615-974-5492
e-mail: JRR@UTK.EDU

BUSINESS CONTACT: Mrs. Chris Cox
Phone: (615) 974-8159

J. Reece Roth

Dr. J. Reece Roth
Principal Investigator

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

TABLE OF CONTENTS

ABSTRACT

During this year, we demonstrated the ability not only to cover the surface of a simulated aircraft fuselage with a thin layer of plasma at one atmosphere in both atmospheric air and helium, but we also demonstrated that this plasma layer would not blow away under the impact of a jet of air from the laboratory service air supply.

These results strongly suggest tha the one atmosphere plasma layer might be useful for boundary layer control and drag reduction on aircraft. This contract has also resulted in 3 issued patents (to which the U.S. government has a royalty-free license); two patent disclosures; two poster paper presentations at conferences, two archival journal publications, and two invited seminar presentations, at the Kirtland AFB and at the NASA-Langley Research Center. It is expected that this work will continue in the wind tunnels at Langley.

INTRODUCTION

This document describes a one-year program of exploratory experimental research on potential aircraft applications of the recently developed one atmosphere uniform glow discharge plasma in air. The research program built on results which were obtained during the last 3 years of AFOSR 89-0319, a 5-year effort under the cognizance of Dr. Robert J. Barker, Code NE, AFOSR, which terminated on March 15, 1994. The results of this previous contract included development of the magnetized plasma cloaking concept (U.S. Patent #4,989,006, Jan. 29, 1991, assigned to the Secretary of the Air Force), and the development of the atmospheric uniform glow discharge plasma (four patent disclosures, three of which have been issued as patents at this writing).

This contract was followed by the current one year contract, AFOSR F49620-94-10249, which conducted an exploratory research program designed to see whether the atmospheric uniform glow discharge plasma can be applied to aircraft in the atmosphere, and, if so, whether such a layer of plasma might be useful for various applications of interest to the Air Force, including plasma cloaking, drag reduction, boundary layer control, or de-icing. These potential applications of the one atmosphere glow discharge plasma to aircraft have been described in patent disclosures which have been included as Appendix B of this report.

During this past year, we demonstrated that a thin layer of plasma can be generated on flat surfaces, including the surface of a cylindrical simulated aircraft fuselage, at one atmosphere, and in ordinary atmospheric air. Moreover, this thin layer of plasma will not be blown away by a jet of air produced from the nozzle of our laboratory air supply.

The organization of this Final Scientific Report includes a section, with photographs, on the physics and phenomenology of the one atmosphere uniform glow discharge plasma. The next section describes potential applications of the one atmosphere

uniform glow discharge plasma to Air Force concerns, and the following section describes our recently-completed 1-year research program. The final two sections describe publications and staffing. Finally, six appendices include the text of 3 patents, two invention disclosures of possible relevance to the Air Force, two conference presentations, two archival publications, and the abstracts of two invited seminars at national laboratories.

THE ONE ATMOSPHERE RF GLOW DISCHARGE

Previous Research

The generation of plasma at one atmosphere is not a recent development. Electrical arcs have been used at one atmosphere since the early 19th Century for various industrial processes, as has the more recently developed plasma torch (ref. 1, 2, 7). The generation of low power density plasmas at one atmosphere also is not new. Filamentary discharges between parallel plates in air at one atmosphere have been used in Europe to generate ozone in large quantities for the treatment of public water supplies since the late 19th century. Such filamentary discharges, while useful for ozone production, are of limited utility because of their nonuniformity, since the plasma filaments tend to puncture exposed materials, the electrode surface insulation, or to promote arcing. The properties of a glow discharge plasma at high pressures, including one atmosphere in air and hydrogen, was reported by von Engle et al. in 1933 (Ref. 3). These discharges were initiated at low pressure (thus requiring a vacuum system), required temperature control of the electrodes, and appear too unstable for routine industrial use or in aircraft cloaking applications. More recently, a group affiliated with Sofia University in Japan (refs. 4-6) has reported the generation of both filamentary and steady state "glow discharge" plasmas at one atmosphere of pressure in gases which include helium and argon with an admixture of acetone, but not atmospheric air. Similar work later originated independently in the UTK Plasma Science Laboratory at the University of Tennessee in Knoxville (refs. 7-11).

The Parallel-Plate One Atmosphere Glow Discharge Reactor

In July, 1991 we initiated an exploratory research program in the UTK Plasma Science Laboratory, under AFOSR contract 89-0319, to develop a RF glow discharge plasma capable of operating at one atmosphere of pressure. The technical means required to produce such a plasma requires some relatively uncommon equipment, most of which was in the inventory of the UTK Plasma Science Laboratory. In the period preceeding January 1992, we built up the apparatus, including our MOD-I (until May, 1993), MOD-II (until October, 1993), and MOD-III (November 1993 to present) parallel plate electrode configurations for the plasma reactor. All three sets of apparatus include a plexiglass box to isolate and control the gas composition between two insulated electrodes. The electrodes in the MOD-I reactor are 21.6 centimeters on a side, and are operated at separations from half a centimeter to five centimeters. We hooked the two parallel plates up to a high voltage RF amplifier capable of operating over the frequency range from 1 kHz to 100 kHz, and of providing up to 5 kW of power at up to 10 kV rms.

Our first plasma was obtained on January 21, 1992 in the MOD-I reactor. We obtained data in both helium and argon gas, as well as argon gas with an admixture of acetone. At 5 kV, we were not able to obtain an RF glow discharge plasma in atmospheric air, because of the much higher breakdown electric field of air. Further exploratory research indicated that we were able to generate a steady state glow discharge at one atmosphere of pressure in helium and argon; that the plasma power levels required ranged from 5 to 100 watts, that the volume of plasma produced could be as large as three liters; and the plate separation could be as great as five centimeters with helium gas. One gratifying aspect of these observations was that the power density was on the order of tens of milliwatts per cm^3 , a relatively low value, much lower than arc discharges or other high intensity plasmas capable of existing in the steady state at one atmosphere pressure. A typical dischage in the MOD-I reactor with helium is shown in Figure 1.

Our exploratory research confirmed that in order to produce a uniform glow discharge, as opposed to a filamentary discharge or streamers, it is necessary to adjust the driving frequency so that the period of the driving frequency is shorter than the ion transit time between the two plates. When this occurs, the ions build up a positive space charge between the electrodes, rather than recombining on the electrode surfaces, and this allows the gas to break down more easily. At frequencies which are so high that both the ion and electron transit times are longer than the period of the driving frequency, the plasma polarizes, and a filamentary electric discharge results. The latter is much less interesting for most applications because of its nonuniformity. Using RMS electric fields of up to 5 kV/cm, we were able to generate a uniform glow discharge plasma at one atmosphere in helium, argon, these two gases with up to 7% oxygen, and nitrous oxide.

In September, 1993, we modified the output transformer windings in our RF amplifier to furnish double the voltage and halve the current to our MOD-II plasma reactor. This allowed us to reach RMS electric fields up to 10 kV/cm. These higher electric fields allowed us to maintain steady-state, uniform one atmosphere glow discharges in atmospheric air and in carbon dioxide. The discharge in air produces enough ozone that we thought it prudent to operate it in a plexiglass enclosure for safety reasons.

On May 28, 1993, we filed two patent disclosures, both of which acknowledged Air Force support. The Air Force and the federal government should be excused from paying any royalty which would otherwise be required by the University for using the industrial technology described in these patents. The first patent describes the basic method, using a high voltage sinusoidal or periodic signal between two insulated parallel plates and operating from one to tens of kilohertz to generate the plasma. The second patent describes what should be a particularly effective method for exposing fabrics to the active species of a one atmosphere glow discharge plasma. These two and a related patent have been issued and are included in Appendix A.

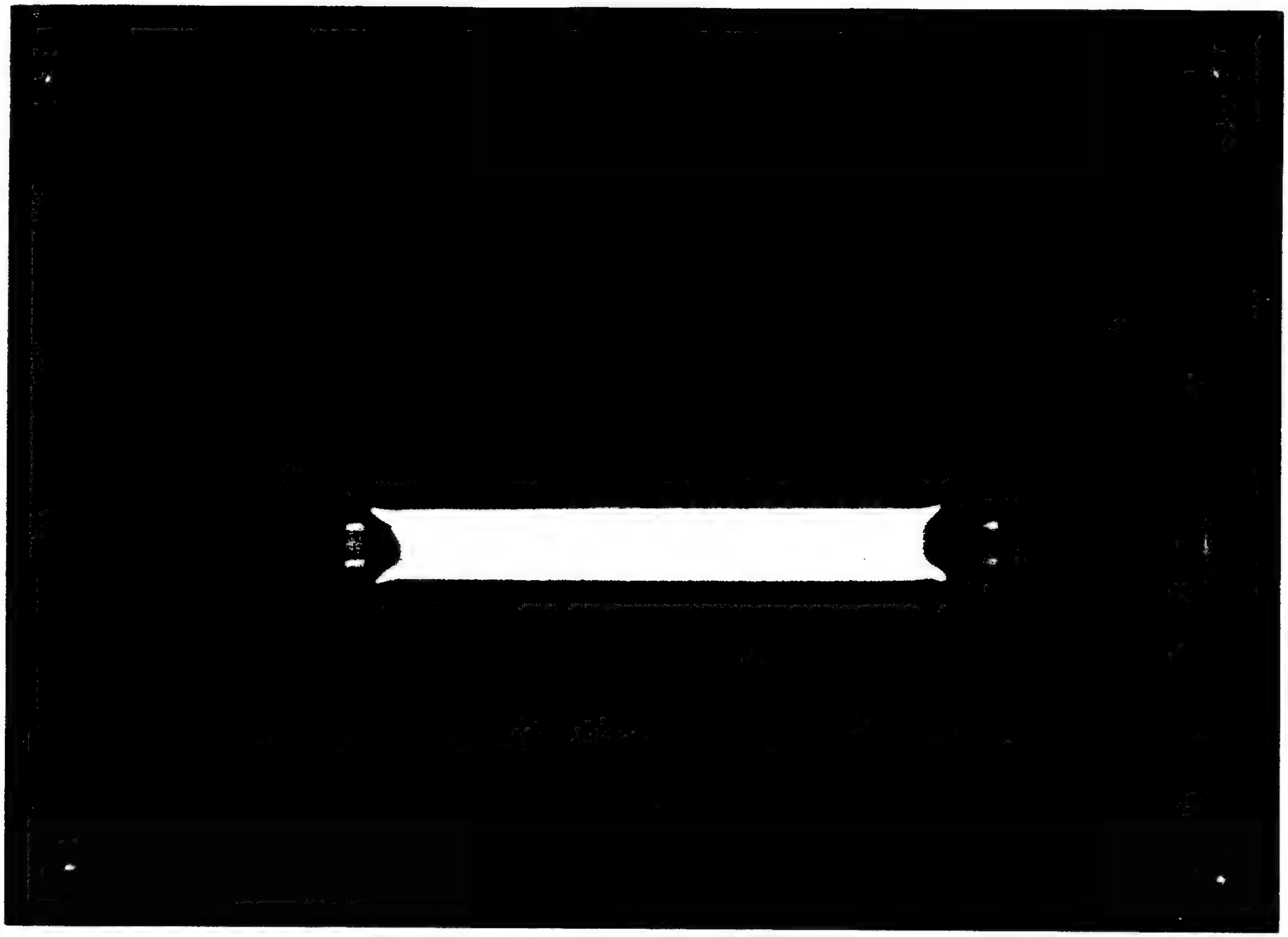


Figure 1. The original, "MOD-I" one atmosphere uniform glow discharge plasma reactor operating with helium gas. The plasma volume is approximately 2.8 liters, the electrodes are 21 centimeters square, and the frequency is 30 kHz.

The "MOD-I" one atmosphere glow discharge plasma reactor developed at the UTK Plasma Science Laboratory with AFOSR support (refs. 7-9) is shown in Figure 1. This reactor consists of two 21.6 cm square, water-cooled copper plates covered with approximately 1 mm of the tough, rubberized material used on the walls of electroplating baths. The approximately 2.8 liter helium plasma shown in Figure 1 was energized at 30 kHz.

More recent work is shown in Figure 2, a photograph of the MOD-III parallel plate reactor, which consists of a lower water-cooled copper plate covered by a sheet of Pyrex, and a bare iron upper plate, shown separated from the Pyrex sheet by two slabs of glass in Figure 2a. Figure 2a shows this parallel plate configuration energized and generating a uniform plasma at one atmosphere in air. The frequency is approximately 2 kHz, and the applied RF voltage is 6 kV rms. Figure 2b shows the same plasma with the laboratory lights out. Note the uniformity of this one atmosphere glow discharge plasma in air.

The physical mechanism which makes possible this uniform glow discharge at one atmosphere is the ion trapping mechanism which has been discussed in previous reports to AFOSR, and in refs. 12 and 13. Reference 12 contains the most complete theoretical discussion of the physics of the one atmosphere uniform glow discharge plasma presently available.

In the parallel plate arrangement, the ion mobility is considerably less than that of the electrons, and it takes a relatively long time for the ions to traverse the unobstructed distance between the two parallel plates in which an electric field exists. The uniform glow discharge plasma is produced when the ions, but not the electrons, are trapped between the two parallel plates. This trapping occurs when the transit time of the ions between the parallel plates is greater than the half-period of the RF voltage applied to the two parallel plates. If one were to increase the RF frequency to the point that both electrons and ions are trapped, the plasma will polarize and form filamentary discharges.

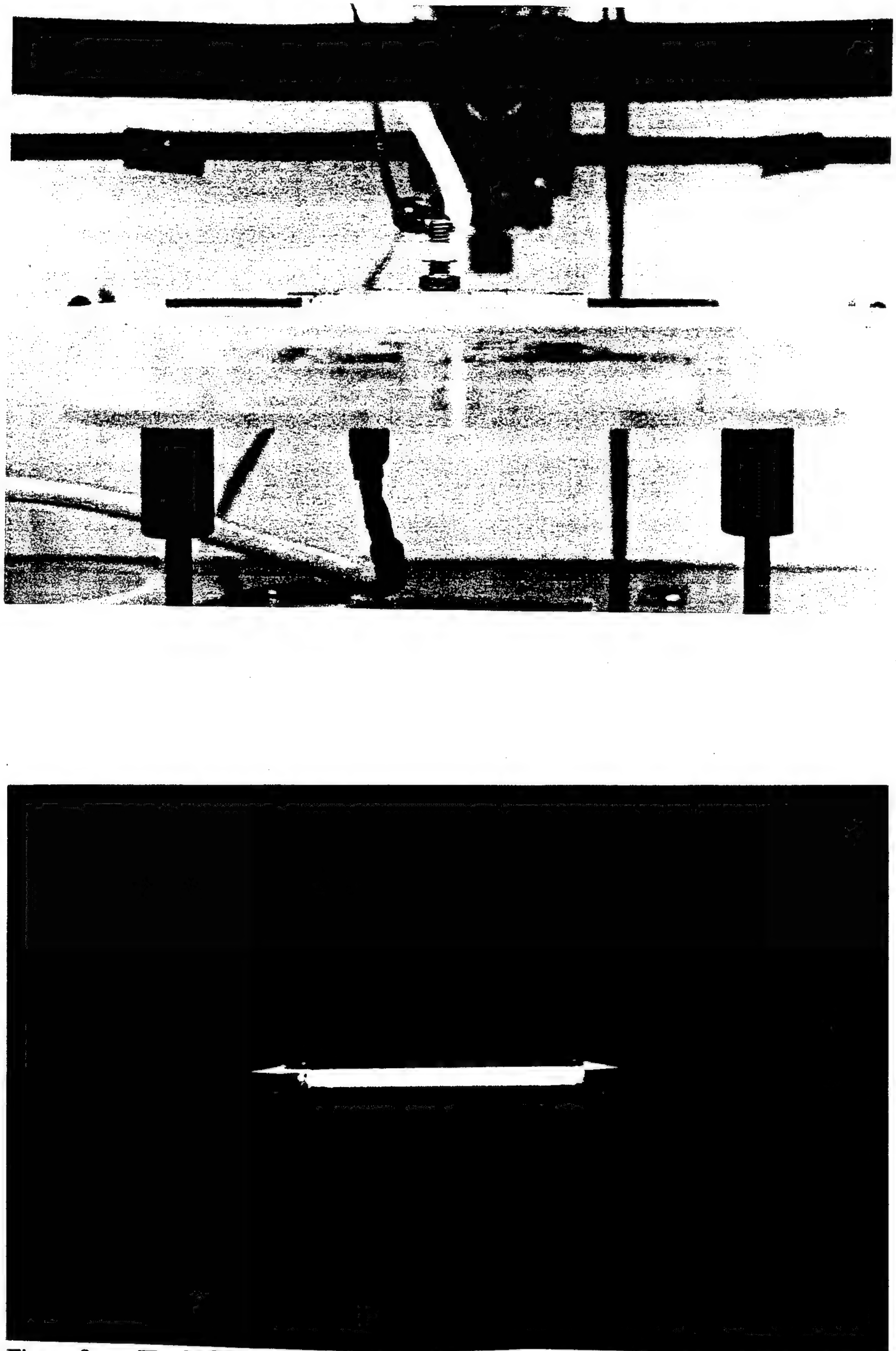


Figure 2. The MOD-III parallel plate one atmosphere uniform glow discharge plasma reactor operating in air. a) This photograph shows the lower, water-cooled electrode covered by a Pyrex plate, and an upper metal plate, supported by two sheets of Pyrex glass, operating in air with a uniform glow discharge plasma. b) same as a above, with the laboratory lights out. Note the uniformity of the plasma.

Generating a One Atmosphere Plasma Surface Layer

The parallel plate configuration shown in Figures 1 and 2, the theory of which is discussed in references 12 and 13, is not suitable for a free-standing body like an aircraft in the atmosphere. In order to cover a free-standing body with a thin surface layer of plasma, we have conceived the planar one atmosphere surface plasma layer reactor shown in Figure 3. In this modification of the one atmosphere uniform glow discharge plasma reactor the RF electrodes, instead of being plane parallel plates opposite one another, are laid down as strip electrodes on a surface, and insulated from each other and from the surface, if the latter is electrically conducting. The electric field lines between each pair of strip electrodes will trap ions, if the frequency of the RF voltage applied to the strip electrodes is sufficiently high that the ion transit time between the strip electrodes is longer than the period of the RF oscillation. As indicated on the right-hand side of Figure 3, the electric field lines trap ions, and thereby generate locally a surface layer of uniform glow discharge plasma at one atmosphere.

The planar geometry shown in Figure 3 was implemented in a cylindrical configuration in the manner shown in the photograph of Figure 4. This photograph shows a five centimeter diameter copper tube which serves as a simulated aircraft fuselage, and the electrodes shown in Figure 3 are created by wrapping a pair of helical wires circumferentially around the cylinder. Adjacent wires are connected to opposite RF polarities, to generate the planar configuration shown in Figure 3. Figure 5 shows the cylinder of Figure 4 energized and operating in helium gas (helium is used because of its relatively low RF breakdown voltage, about 2.5 kilovolts per centimeter, as compared to approximately 8 kV per centimeter for air). The windings in Figure 5 were energized at 3 kHz and with an rms voltage of 3 kV.

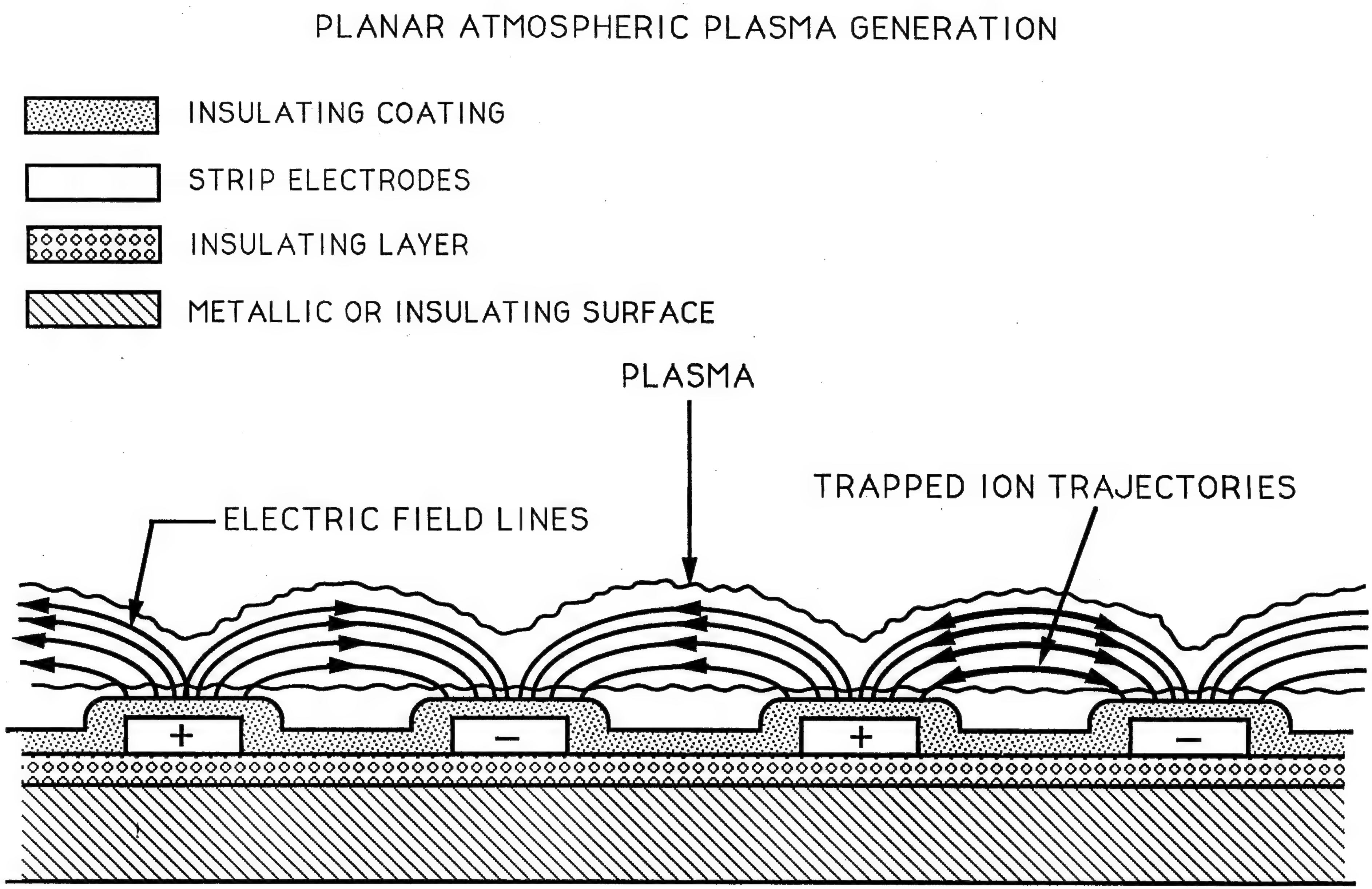


Figure 3. The planar surface layer plasma reactor. Ions are trapped along the electric field lines between adjacent strip electrodes, which are maintained at opposite RF polarities.

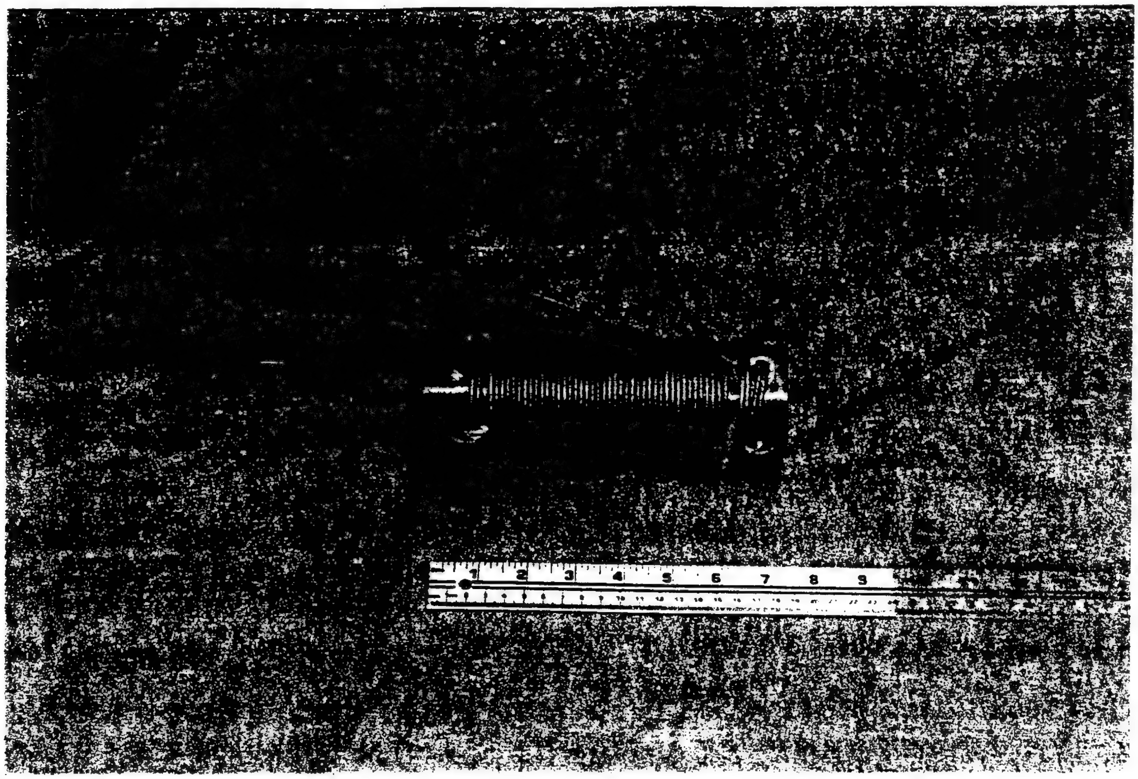


Figure 4. A planar surface layer plasma reactor on a 5 centimeter diameter simulated aircraft fuselage. The pair of bifilar wires is wrapped helically on the surface of the cylinder, providing adjacent electrodes of opposite polarity as indicated in Figure 3.

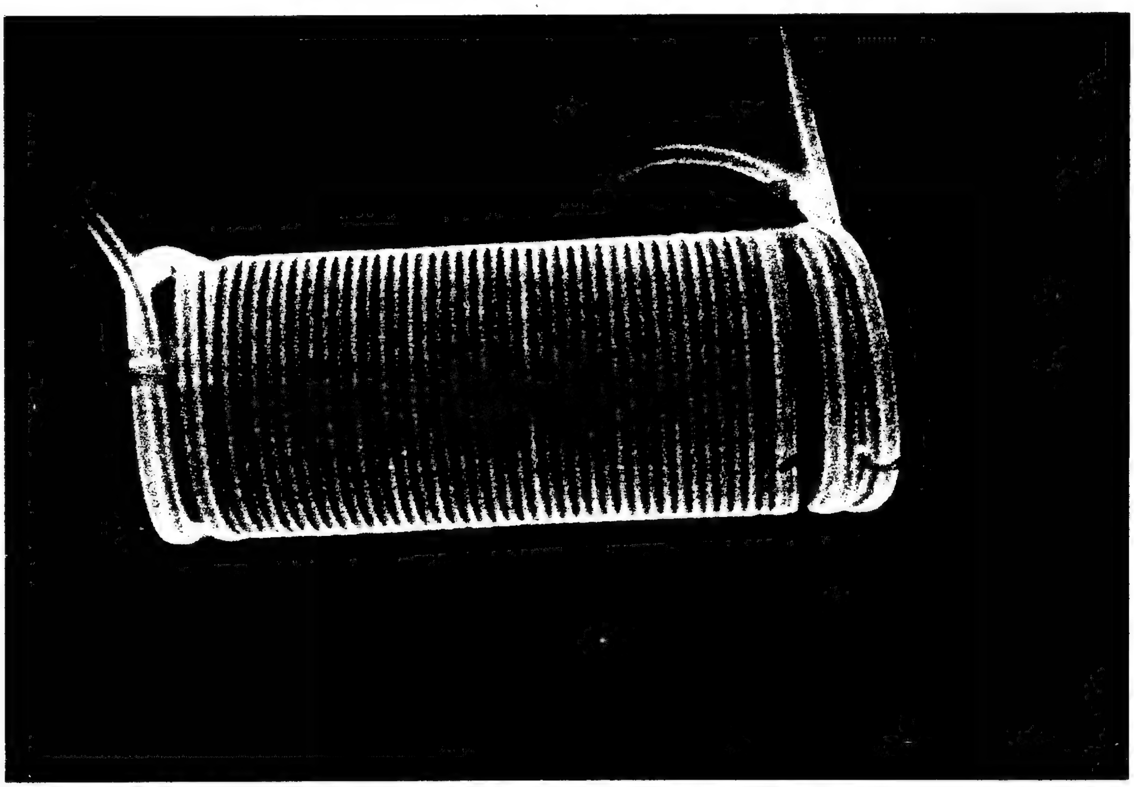


Figure 5. The simulated aircraft fuselage shown in Figure 4, operating in helium gas, at a frequency of three kilohertz, and three kilovolts, rms.

Plasma Parameters of the One Atmosphere Uniform Glow Discharge

Even when one has a large volume of steady state plasma, as shown in Figure 1 with the MOD-I parallel plate plasma reactor, the diagnosis of the plasma characteristics at one atmosphere is not an easy matter. For example, normal Langmuir probe theory cannot be applied, because at one atmosphere the electron mean free paths are less than the Debye distance in the sheath surrounding the Langmuir probe. Similarly, one cannot use ordinary microwave interferometric methods, because at one atmosphere the electron collision frequencies are terahertz, well above the microwave frequencies of interest in radar and communications applications. Nonetheless, we have made a start at diagnosing the plasma parameters in a parallel plate configuration similar to that shown in Figure 1. This work has been supported for the most part by the UTK Textiles and Nonwovens Development Center (TANDEC). The number density measurements were made by Dr. Paul D. Spence, using an electromagnetic absorption technique that makes use of the high collision frequencies in order to obtain an estimate of the electron number density. The power densities measured were based on integrating the voltage and current after the reactive power was subtracted from the appropriate waveforms. One key plasma parameter that we do not have a good measurement of at this time is the electron kinetic temperature. The electrons must be energetic enough to produce visible line radiation at several eV, and a significant population of electrons must be energetic enough to produce ionization in helium or air. On this basis, we estimate the electron kinetic temperature at some value between one and 20 electron volts, although a proper measurement of this parameter remains one of our outstanding and high priority diagnostic problems.

The approximate characteristics of the one atmosphere uniform glow discharge plasma as generated in a parallel plate configuration are indicated in Table I.

Table I

Plasma Characteristics of the One Atmosphere Uniform Glow Discharge

Electron Number Density e/m^3	$\approx 1 \times 10^{16}$
Neutral Number Density, $/m^3$ (1 Atmosphere)	2.7×10^{25}
Electron Kinetic Temperature, eV	$1 \leq T_e' \leq 25$
Ion Kinetic Temperature, eV	≈ 0.025
Plasma power density, mW/cm^3	4-120
Total Plasma Power, Watts	$10 \leq P \leq 150$
RF Frequency, kHz	$1 \leq \nu \leq 30$
RMS Electric Field, Volts/cm	$1 \leq E \leq 20$

We have very little information about the ion energies, but because of the high ion collision rates, and the good energy coupling between the ion population and the neutral background molecules, it seems a safe assumption that the ion kinetic temperature is essentially that of room temperature, 0.025 eV. Measurements on a helium plasma have revealed that the power density in a planar reactor is on the order of tens of milliwatts per cubic centimeter. This power density is low enough for a surface plasma to be generated on an aircraft by utilizing only a few percent of the shaft horsepower generated in a typical aircraft engine.

POSSIBLE UTILITY OF RESEARCH TO THE AIR FORCE

The development, under the auspices of this and previous AFOSR contracts, of a uniform RF glow discharge at one atmosphere in air and other gases has potential Air Force applications in at least three areas. The first is industrial plasma engineering, including the

improvement of the wettability and wickability of polymer films and fabrics; the second is the generation of a plasma layer over the surface of aircraft for the purpose of electromagnetic plasma cloaking, and the third is use of the electromagnetic body force on a plasma layer surrounding an aircraft for drag reduction and boundary layer control.

The industrial plasma engineering applications were covered in two patent disclosures filed on May 28, 1993, and in amendments to these two disclosures filed on October 29, 1993. These disclosures recognize the support of AFOSR, and the Air Force and the federal government will be entitled to a royalty-free license to the resulting patents. Three of these disclosures have been issued as patents by the U.S. Patent Office, and the fourth is pending at the time of writing. The text of these patents has been included in Appendix A.

The applications to plasma cloaking of aircraft were described in recent patent disclosures. A decision was taken by the University of Tennessee's Research Corporation (UTRC) <u>and</u> by the Air Force Patent Office at Hanscom AFB, MA not to pursue the cloaking disclosure, which is Appendix B, Section B-3.

The applications of an atmospheric glow discharge plasma layer to drag reduction and aerodynamic boundary layer control on aircraft are described in two patent disclosures reproduced in Appendix B, B-1 and B-2. The role of AFOSR support in these is also acknowledged, and the Air Force will be entitled to a royalty-free license for their use. The UTRC is currently pursuing patents for the disclosures in Appendix B, B-1 and B-2.

<u>Applications to Industrial Plasma Engineering</u>

One of the most rapidly growing new fields in the industrial infrastructure is industrial plasma engineering. The industrial uses of plasma are motivated by its ability to accomplish industrially relevant results more efficiently and cheaply than competing processes; by its ability to perform tasks which can be accomplished in no other way; and

by its ability to accomplish results without producing large volumes of waste material or toxic byproducts (refs. 1 and 2). Many of these applications utilize the active species generated by glow discharge plasmas.

A major impediment to the industrial use of glow discharge plasmas for the surface treatment of materials is that such glow discharges are typically operated in vacuum systems at pressures below ten torr. This requirement for low pressure operation has led, in the microelectronics industry, to plasma reactors, the capital and operating costs of which are dominated by elaborate and expensive vacuum systems which enforce batch processing, rather than more desirable continuous processing.

As described above, we have developed a one atmosphere RF glow discharge plasma reactor at the UTK Plasma Science Laboratory which will allow the generation of a glow discharge with power densities on the order of 10's of milliwatts per cubic centimeter or higher in helium, air, and other gases at one atmosphere pressure. These one atmosphere glow discharge plasmas produce active species which can have very significant effects on the wettability, wickability, and printability of various fabrics (ref. 9,12). These results offer promise that the characteristics of many fabrics can be altered in ways useful to Air Force missions; fabrics which are currently fire retardent and flame proof can be made more wettable and hence more comfortable to wear; adhesive bonding to fabrics may be improved; and the bonding of matrix binders to reinforcing fabrics may be improved in composite materials used for aircraft skin and structure. Another potential Air Force application of an atmospheric glow discharge could arise from the circumstance that the Air Force, as well as other branches of the Department of Defense, are under heavy pressure to reduce the volume of ordinary and toxic industrial wastes which result from the production of weapons and weapon systems. The plasma chemistry associated with such atmospheric discharges may facilitate this.

Applications to Plasma Cloaking

The disclosure included in Appendix B, as Section B-3, describes a method of passive plasma cloaking of military targets in the atmosphere which utilizes a uniform surface layer of one atmosphere glow discharge plasma generated by low frequency RF fields. Such a layer of plasma could simultaneously serve several objectives. It could provide a protective layer against high power directed electromagnetic energy weapons, since, at many wavelengths, a plasma is a far stronger absorber than an equivalent thickness of neutral atmosphere. Such a plasma layer could also serve as a shield against an electromagnetic pulse designed to damage or disable receivers and sensitive electronic equipment on the target. Such a layer could further serve to absorb, scatter, or reflect in other directions radar pulses interrogating the target from ground-based radar or radar-guided weapons.

The principal difference between the one atmosphere parallel plate industrial plasma reactor and the aircraft plasma is the method of generating the RF electric field above the surface of the vehicle. Modifications of the parallel plate arrangement are necessary in a freely moving vehicle in the atmosphere, to make it possible to sustain electric fields near the surface of the vehicle in excess of approximately 10 KV per centimeter, needed to produce a uniform glow discharge at one atmosphere in air or other gases.

As discussed above in connection with Figure 3, the electrodes used to create the one atmosphere glow discharge plasma can be arranged in parallel strips on the surface, insulated from the aircraft surface and each other, with adjacent strips being operated at radio frequency voltages 180^{o} out of phase with each other, and at sufficiently high RF voltages that RMS electric fields of 10 kilovolts per centimeter are generated a few millimeters above the surface of the vehicle. Such an array of strip electrodes is shown in Figure 6. The width of the individual strip electrodes should be wide enough to create a uniform plasma layer over the surface of the vehicle. The strip electrodes can be oriented

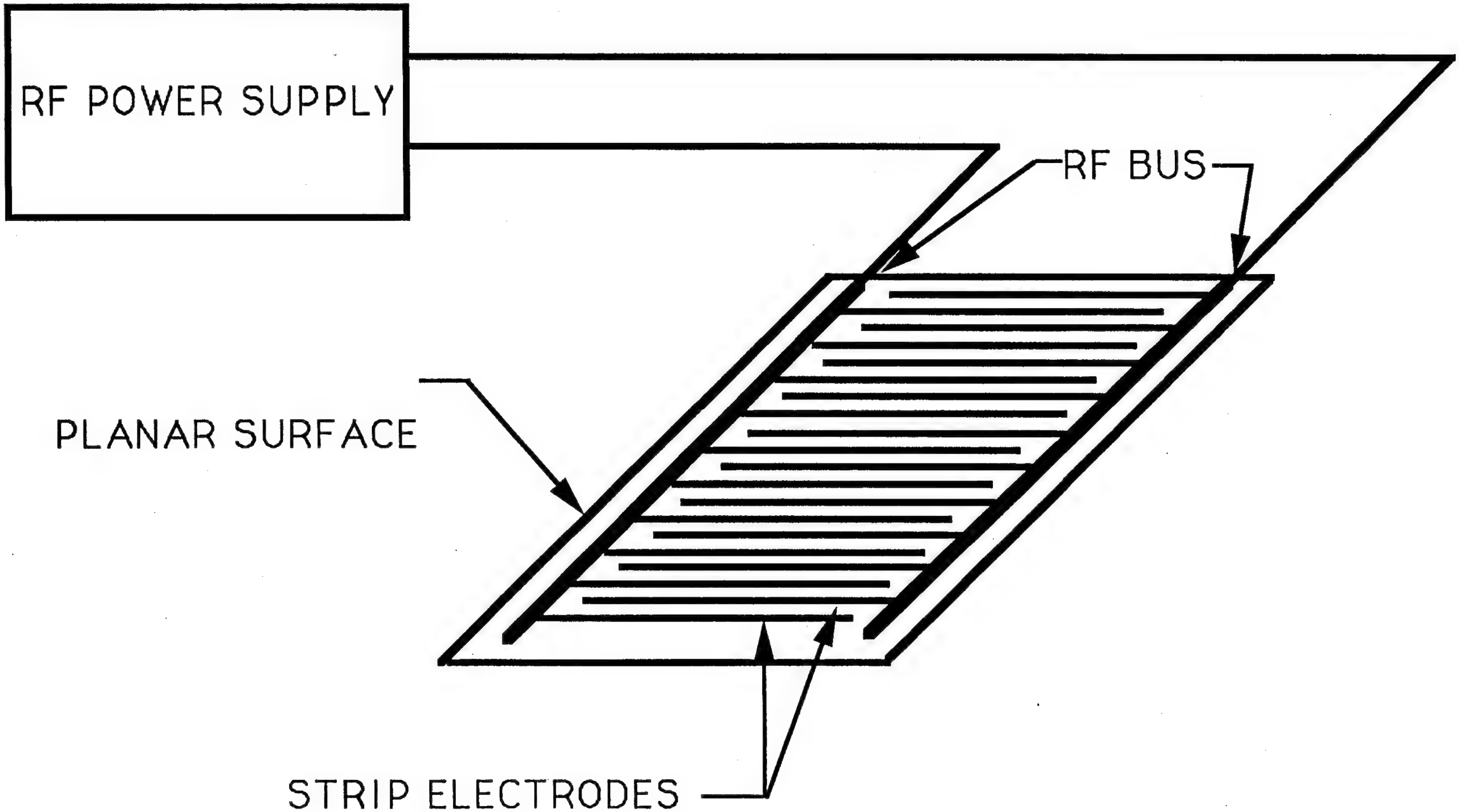


Figure 6. Simple stripped electrode arrangement for a planar atmospheric plasma surface layer.

on the surface of the vehicle as a matter of convenience, in a quasi-parallel pattern, or the electrodes might be placed parallel or perpendicular to the aerodynamic velocity vector in the boundary layer flowing over the surface of the vehicle. The width of individual strip electrodes may be adjusted over the surface of the aircraft, in such a way as to produce dense plasma where it is most needed, and more rarefied plasma where that is satisfactory for the intended application of the plasma layer.

For the plasma cloaking application, the interaction of incident electromagnetic radiation with the plasma layer, and the cloaking effect of the plasma layer, would result from the characteristically strong interaction between the incident RF electromagnetic field and the plasma electron population. Strong attenuation of incident electromagnetic signals would be anticipated as a result of the very high electron-neutral collision frequencies at one atmosphere, frequencies that are characteristically in the terahertz range. In addition to attenuation, other plasma-electromagnetic interactions would occur, depending on whether the incident radiation is above or below the electron plasma frequency of the plasma layer. Electron number densities in the plasma layer at one atmosphere are anticipated to be as much as 10^{12} electrons per cubic centimeter or higher. Such number densities may lead to strong interactions with all microwave and RF frequencies below approximately 9 GHz.

It is anticipated that the electron plasma frequency for the plasma layer can be adjusted by increasing or decreasing the electron number density through control of the power density dissipated in the plasma layer. Thus, by increasing or decreasing the power density dissipated in the plasma layer, the electron plasma frequency can be adjusted in such a way as to be above the highest anticipated probing frequency used by a potential adversary. Such a plasma layer can be maintained at relatively small cost in energy, power densities from 10 to 100 milliwatts per cubic centimeter having been typical in laboratory experiments on a parallel plate one atmosphere glow discharge plasma reactor. The plasma layer is a passive cloaking mechanism, since once it is turned on, it provides continuous

protection against probing electromagnetic radiation up to frequencies at last equal to the electron plasma frequency in the surface plasma layer, and possibly beyond. The pulsed energy load dumped in the plasma layer in the case of directed electromagnetic energy weapons or an electromagnetic pulse (EMP) may be convected away by the aerodynamic gas flow over the surface of the aircraft or other vehicle as it moves through the atmosphere.

The apparatus required to generate a one atmosphere glow discharge plasma around vehicles in the atmosphere is indicated schematically on Figures 3 and 6. A low frequency RF power supply capable of operating from a few hundred hertz to 20 KHz at RMS voltages up to 20 KV is connected to the fuselage of the aircraft to be energized, and the other RF terminal connected to a reference electrode, as discussed above. Alternatively, adjacent electrodes can be energized at opposite RF polarities, as diagrammed in Figure 3. These connections are made through an impedance matching network, the function of which is to minimize the reactive power in the RF circuit. The fuselage of the vehicle may be coated with an electrically insulating coating, if necessary.

Previously reported measurements on a parallel plate uniform glow discharge plasma reactor operating at atmospheric pressure indicated that such glow discharges could be maintained by average power densities ranging fromm below 10 milliwatts per cubic centimeter to values higher than 100 milliwatts per cubic centimeter. On the basis of these experiments, it is reasonable to suppose that a power density of 50 milliwatts per cubic centimeter may be required to maintain a layer of plasma surrounding an aircraft. If the aircraft has a total surface area of 200 square meters, and if the layer of plasma is two millimeters thick, 0.40 cubic meters of plasma would need to be generated at 50 milliwatts per cubic centimeter. This would require an energy input to generate such a plasma of 20 KW, a power level about 0.20 percent of the total skin friction drag on such a typical aircraft. Thus, there appears to be no reason, on energetic grounds, why full-scale aircraft

should not be able to supply the power requirements for generating such a uniform plasma over their surface, at an energy cost in shaft horsepower that is less than one percent of that developed for their flight requirements. Even in an extreme case, the mass of the electrical power generator and power supplies required to produce the high voltage RF needed to produce the plasma should require no more than about 1 kilogram per kilowatt, thus burdening the aircraft in the example above with no more than about 20 kilograms of additional equipment.

The discussion in the previous paragraph indicates that the power requirements for coating the surface of an aircraft for either cloaking or drag reduction applications should not be too great to be supplied by normal onboard power generation. Another point to be made about application of the surface plasma layer to aircraft is that the generating scheme indicated schematically in Figure 3 can be retrofitted to existing aircraft, at least for testing purposes, and does not require the construction of an entirely new aircraft using exotic technologies. The ability to put strip electrodes on the surface of existing aircraft may prove to be a major developmental benefit during early proof of principle and testing stages.

Applications To Drag Reduction

The disclosures included in Appendix B, Sections B-1 and B-2, describe a method for covering the surface of aircraft or other vehicles moving in the atmosphere with a steady state, uniform, glow discharge plasma for the purpose of boundary layer control and reducing their aerodynamic drag. Such a layer of plasma is capable of transmitting an electrostatic body force to the aerodynamic boundary layer. Such a body force may reduce the level of boundary layer turbulence and/or suppress the formation of turbulent vortices, thus reducing the drag coefficient of the aircraft in the atmosphere, and eliminating other

consequences of turbulence in the boundary layer above the skin of the aircraft, including aerodynamic noise.

It is proposed to utilize the previously discussed mechanism for the formation of a plasma layer on the skin of aircraft, or other high speed vehicles which move in the atmosphere. Several different arrangements for implementing such conditions near the surface of a vehicle moving in the atmosphere have been discussed above. By turning the plasma on and off, and varying the intensity of the plasma through the input power density and the applied RF voltage, it should be possible to vary the drag coefficient of the aircraft from the normal value without the plasma layer, to values which may be much lower than those normally encountered. The plasma would tend to be swept along with the aerodynamic boundary layer flow, and would tend to accumulate in areas of stagnation or in vortices, thus making these aerodynamically drag-producing structures subject to an electric field, which may be manipulated by auxiliary or control electrodes on the surface of the aircraft.

In addition to reducing the drag and manipulating the geometry and position of vortices and areas of stagnant aerodynamic flow, the boundary layer may be either speeded up or slowed down by traveling electrostatic (peristaltic) waves, in which regions of higher than average electric field are caused to flow over the surface of the aircraft in the direction of the aerodynamic flow, thus exerting an electrostatic body force on the aerodynamic flow in the boundary layer, speeding it up or slowing it down, and further reducing the drag coefficient between the aircraft and the surrounding atmosphere. The induction of peristaltic waves of plasma and/or neutral boundary gases can be accomplished by covering the surface of the aircraft with a series of insulated strip electrodes, oriented perpendicular to the normal aerodynamic flow of the boundary layer gases over the aircraft, as shown in Figure 6. These strip electrodes could then be energized in sequence, to exert an

acceleration of the plasma in the boundary layer, thus making the flow more laminar, and discouraging the formation of vorticity.

In the same way just described, the phasing of the RF voltage on adjacent parallel electrodes could be adjusted to decelerate as well as accelerate the boundary layer, thus producing an accelerating or braking effect on the motion of the aircraft through the atmosphere.

Various elaborations of this plasma-related boundary layer control can be envisioned. The surface of the aircraft or vehicle might be fitted with a series of parallel insulated electrodes, the contours of which are perpendicular to the most laminar and least turbulence-producing boundary layer flow over the aircraft, as determined by wind tunnel tests. Phased excitation of these contoured parallel insulated electrodes could provide a body force accelerating the boundary layer flow over the aircraft in a direction which is least likely to lead to turbulence and vortex formation. Such manipulation of the boundary layer by electrostatic body forces may, in addition, have the effect of raising the Reynolds number for transition to turbulent flow both locally, and for the aircraft as a whole.

RESEARCH PROGRAM

Exploratory Development of Industrial Plasma Engineering Applications

We have investigated the effects of treating various fabrics and polymer films with the active species from a glow discharge plasma, but not under the AFOSR contract. These investigations will be supported by the Textiles and Nonwovens Development Center (TANDEC) of the UTK College of Human Ecology and other industrial sources. The availability of fabric expertise at TANDEC has already proven very useful in identifying and quantizing the effects of exposure to a one atmosphere glow discharge plasma of several nonwoven fabrics. Some of the most recent of this research is described in Ref. 12, a reprint of which is in Appendix E. We expect to interact not only with TANDEC, but

also with various industrial sponsors, several of which have already expressed an interest in the significant increase in wettability and wickability of nonwoven fabrics which has resulted from exposure to our plasma.

The plasma exposure and testing for wettability of thin plastic films (provided by Dr. Larry Wadsworth, TANDEC) was carried out during the Spring semester, 1995 by Ms. Anna Carr, a ECE Senior Project student. It was found that only a minute or so of exposure to a one atmosphere air plasma would make all films wettable, as determined by the contact angle of a sessile water drop test. It was also found that newsprint could be made more wettable, and that smearable ink could be fixed by plasma exposure so that it no longer smeared.

Exploratory Development of Plasma Assisted Drag Reduction for Aircraft

Because of the potential importance of boundary layer control and aircraft drag reduction to the Air Force, we conducted a series of exploratory experiments on the plasma-covered simulated aircraft fuselage shown in Figure 5. It was found that the plasma layer could not be blown away by a jet of air from the laboratory air supply, and that when it was sprayed with water (a simulated rainstorm), the plasma layer quenched, but then rapidly boiled away the water within 10 seconds or so. These results were reported in the poster paper which is included in Appendix E as Section E-2.

The subject of plasma assisted drag reduction for aircraft is obviously of potential interest and importance to the Air Force. For that reason, the Principal Investigator opened negotiations with several organizations which appear to be interested in possible use of the one atmosphere uniform glow discharge plasma for boundary layer control, drag reduction, and noise reduction of aircraft. I have contacted Mr. Steven Wilkinson and Dr. Leonard Weinstein of the NASA Langley Research Center, who appear to be interested in this concept. Indeed, I learned in my conversations with personnel at the Langley Research

Center that Dr. Weinstein had in the past done wind tunnel measurements on the use of one atmosphere corona discharges for drag reduction. These investigations showed that corona discharges could reduce drag, but they were not scalable to higher plasma densities, in the way that the one atmosphere uniform glow discharge plasma is. I have also sent some photographs and reprints of papers on the subject to Dr. James H. Degnan of the Phillips Laboratory at Kirtland Air Force Base, New Mexico. During February and March, 1995, the Principal Investigator gave seminars on aerodynamic boundary layer control with an atmospheric plasma layer at the Kirtland Air Force Base, NM, and at the NASA Langley Research Center at Hampton, VA. The abstracts of these seminars are in Appendix F.

As a result of this outreach, a joint proposal involving the P.I. and Mr. Steven Wilkinson of Langley has been submitted to the Director of Langley. If funded, this effort will support wind tunnel tests on a flat plate covered with a plasma layer.

If any of these initiatives work out, I expect that we will have a synergestic effort on aerodynamic boundary layer control which can be applied to the plasma cloaking application. Indeed, if everything works out favorably, it may be possible to use a plasma boundary layer on aircraft for cloaking purposes, as well as drag reduction and aerodynamic noise control.

PUBLICATIONS AND OTHER INTERACTIONS

Patents

During the period of this contract, 3 patents were issued which were filed under previous AFOSR contracts. As a result of AFOSR sponsorship, the U.S. Government has a royalty-free license to this technology. The full text of these patents is included in Appendix A.

Patent Disclosures

During the period of this contract, 3 patent disclosures were written. Their text is included in Appendix B. Disclosures B-1 and B-2 were filed by the UT Research Corporation. Disclosure B-3, on plasma cloaking with a one atmosphere plasma layer, was not filed, upon election by UTRC and the Air Force Patent Office at Hanscom AFB, MA. As a result of AFOSR support, the U.S. Government will have a royalty-free license to any patents resulting from disclosures B-1 and B-2.

Poster Presentations

During this contract year, two poster presentations were made at plasma meetings. These are listed as references 14 and 15. The abstracts are in Appendix C, and the full texts of the poster presentations is included in Appendix D.

Archival Publications

During this contract year, two AFOSR-supported archival publications appeared. These are listed as references 12 and 16, and their full text is included as Appendix E.

Seminars at Other Laboratories

During this contract year, the Principal Investigator gave formal seminars at the Kirtland AFB, NM, and at the NASA Langley Research Center, Hampton, VA. The seminars were on the subject of aerodynamic boundary layer control and drag reduction with an atmospheric plasma layer. The abstracts and meeting announcements of these seminars are included in Appendix F. The interaction with NASA-Langley has resulted in a proposal to Langley management for wind tunnel work.

STAFFING

Principal Investigator

Dr. J. Reece Roth obtained a S.B. in Physics from M.I.T. in 1959, where he held a four-year Alfred P. Sloan Scholarship. He obtained the Ph.D. from Cornell University in 1963 where he was a Ford Fellow, with a major in Engineering Physics. He joined the NASA Lewis Research Center in Cleveland, Ohio in 1963, where he conducted research on high temperature plasma physics and space power and propulsion systems. He joined the faculty of the Electrical and Computer Engineering Department at the University of Tennessee, Knoxville in 1978, where he is a full professor. Dr. Roth is a Fellow of the IEEE, an Associate Fellow of the AIAA, and has served on many elective and appointive posts in these and other professional societies of which he is a member.

In the past thirty-five years, Dr. Roth has authored two textbooks; authored or co-authored 131 archival publications, of which 47 were articles in refereed journals, 47 were full-length papers in reviewed conference proceedings, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Spacecraft and Rockets, Fusion Technology, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 137 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work.

Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity-equation oscillation has

been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. 1. Dr. Roth was also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August 1979.

Dr. Roth has recently attended conferences on plasma chemistry, and published on plasma materials processing. Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnet facilities in plasma and fusion applications; the continuity-equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; fusion technology; and industrial plasma engineering. Dr. Roth's academic responsibilities have included teaching a required undergraduate course on plasma engineering from his own notes; a one-year senior and graduate level sequence on fusion energy, also from his own notes; a one year graduate course in plasma diagnostics which includes a laboratory; a graduate level course on industrial plasma engineering, from his own notes; a doctoral level course on advanced plasma physics; and intensive one-week minicourses on Fusion Diagnostics, Fusion Energy, and Industrial Plasma Engineering which have attracted students from all over the United States and 9 foreign countries. He has published a textbook, "Introduction to Fusion Energy" which is now in its fifth printing. This book also has a Chinese edition, which was published by the Tsinghua University Press, Beijing, in 1993. Dr. Roth is currently working on a two-volume textbook, "Industrial Plasma Engineering", which is under contract for publication. The first volume was published in January, 1995.

Graduate Research Assistant

The staffing level at the UTK Plasma Science Laboratory was one graduate research assistant. Mr. Chaoyu Liu was supported until December, 1994. The work was continued until the end of the contract by Ms. Anna Carr, an ECE senior project student.

REFERENCES

1. Roth, J. R.: Industrial Plasma Engineering: Volume I-Principles. Institute of Physics Press, Bristol, U.K. (1995) ISBN 0-7503-0317-4.

2. Roth, J. R.: Industrial Plasma Engineering: Volume II-Applications. Institute of Physics Press, Bristol, U.K. (to be published, 1997).

3. Von Engle, A.; Seeliger, R.; and Steenbeck, M.: On the Glow Discharge at High Pressure. Zeit. fur Physik, Vol. 85 (1933) pp. 144-160.

4. Kanazawa, S; Kogoma, M.; Moriwaki, T.; and Okazaki, S.: Stable Glow Plasma at Atmospheric Pressure, J. Physics D., Vol. 21 (1988) pp. 838-840.

5. Yokoyama, T.; Kogoma, M.; Moriwaki, T.; and Okazaki, S.: The Mechanism of the Stabilization of Glow Plasma at Atmospheric Pressure, J. Physics D., Vol. 23 (1990) pp. 1125-1128.

6. Kanda, N.; Kogoma, M.; Jinno, H.; Uchiyama, H.; and Okazaki, S.: Atmospheric Pressure Glow Plasma and its Application to Surface Treatment and Film Deposition Paper 3.2-20, Proc. 10th International Symposium on Plasma Chemistry, Vol. 3 (1991) pp. 3.2-201 to 3.2-204.

7. Roth, J. R.; Liu, C.; and Laroussi, M.: Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure. Paper 5P-21, Proc. 1992 IEEE International Conference on Plasma Science, Tampa, FL, IEEE Catalog No. 92-TH0460-6, ISBN 0-7803 0716-X (1992). pp. 170-171.

8. Liu, C.; Chen, D.; and Roth, J. R.: Characteristics of a Steady-State, Low-Power Glow Discharge at Atmospheric Pressure. APS Bulletin Vol. 37, No. 6 (1992) p. 1563.

9. Liu, C.; Tsai, P.P.-Y.; and Roth, J. R.: Plasma Related Characteristics of a Steady-State Glow Discharge at Atmospheric Pressure. Paper 2P-18, Proc. 1993 IEEE International Conference on Plasma Science, Vancouver, B. C. IEEE Catalog No. 93-CH3334-0, ISBN 0-7803-1360-7 (1993) p. 129.

10. Roth, J. R.; Spence, P. D.; and Liu, C.: Preliminary Measurements of the Plasma Properties of a One Atmosphere Glow Discharge Plasma. APS Bulletin Vol. 38, No. 10 (1993) p. 1901.

11. Roth, J. R.; Wadsworth, L. C.; Spence, P. D.; Tsai, P. P.-Y; and Liu, C.: A One Atmosphere Glow Discharge Plasma for Surface Treatment of Nonwoven Fabrics. Proc. 3rd Annual Tandec Conference, Nov. 1-3, 1993 Knoxville, TN.

12. Tsai, P. P.-Y.; Wadsworth, L. C.; Spence, P. D.; and Roth, J. R.: "Surface Modifications of Nonwoven Webs Using One Atmosphere Glow Discharge Plasma to Improve Web Wettability and Other Textile Properties". Proc. 4th Annual TANDEC Conference, Nov. 14-16, 1994, Knoxville, TN.

13. See Reference 6 above, Chapter 12, pp. 453-461.

14. Liu, C. and Roth, J. R.: Applications of the One Atmosphere Glow Discharge Plasma to Illumination and Aerodynamic boundary Layer Control. APS Bulletin, Vol. 39, No. 7 (1994) p. 1730.

15. Roth, J. R.: Boundary Layer Control by a One Atmosphere Uniform Glow Discharge Plasma Layer. Proc. 1995 IEEE International Conference on Plasma Science, IEEE Catalog No. 95CH35796, ISSN 0730-9244 (1995) p. 251.

16. Roth, J. R.: "Ball Lightning: What Nature is Trying to Tell the Plasma Research Community." Fusion Technology, Vol. 27, (1995) pp. 255-270.

17. Roth, J. R.: "Boundary Layer Control by a One Atmosphere Uniform Glow Discharge Plasma Layer," Kirtland AFB, Albuquerque, NM, March 6, 1995.

18. Roth, J. R.: "A New Atmospheric Glow Discharge for Fluid Mechanical Control Using a Plasma Surface Layer"-NASA Langley Research Center, February 24, 1995.

APPENDIX A

Issued Patents

US005387842A

United States Patent [19]

Roth et al.

[11] Patent Number: 5,387,842

[45] Date of Patent: Feb. 7, 1995

[54] STEADY-STATE, GLOW DISCHARGE PLASMA

[75] Inventors: John R. Roth; Peter P. Tsai; Chaoyu Liu, all of Knoxville, Tenn.

[73] Assignee: The University of Tennessee Research Corp., Knoxville, Tenn.

[21] Appl. No.: 68,508

[22] Filed: May 28, 1993

[51] Int. Cl.[6] H01J 7/24; H05B 31/26

[52] U.S. Cl. .... 315/111.21; 118/723 E; 313/231.31; 204/298.04

[58] Field of Search .... 315/111.21, 111.51; 118/723 E; 204/298.04; 219/121.1; 313/231.31

[56] References Cited

U.S. PATENT DOCUMENTS

4,469,932	9/1984	Spiegelberg et al.	313/231.31
4,687,573	8/1987	Miller et al.	210/143
4,771,730	9/1988	Tezuka	118/723 E
4,919,968	4/1990	Buhl et al.	219/121.11
5,213,658	5/1993	Ishida	118/723 E

FOREIGN PATENT DOCUMENTS

0200529	11/1983	Japan	315/111.21
1177374	8/1986	Japan	118/723 E
0312223	12/1990	Japan	315/111.21

OTHER PUBLICATIONS

Authors: Naoki Kanda, Masuhiro Kogoma, Hiroshi Jinno, Hiroshi Uchiyama and Sachiko Okazaki Title: Atmospheric Pressure Glow Plasma and Its Application to Surface Treatment and Film Disposition Publication: International Union of Pure and Applied Chemistry. 10th International Symposium on Plasma Chemistry. Symposium Proceedings, vol. 3, Bochum, Germany, Aug. 4–9, 1991.

Authors: M. Kogoma, H. Kasai, K. Takahashi, T. Moriwaki and S. Okazaki Title: Wettability Control of a Plastic Surface by CF_4–O_2 Plasma and Its Etching Effect Publication: J. Phys. D: Appl. Phys., vol. 20, (1987).

Authors: S. Kanazawa, M. Kogoma, T. Moriwaki and S. Okazaki Title: Stable Glow Plasma at Atmospheric Pressure Publication: J. Phys. D: Appl. Phys., vol. 21 (1988).

Author: Chaoyu Liu Title: Plasma-Related Characteristics of a Steady-State Glow Discharge at Atmospheric Pressure Publication: Presented at the 1993 Sigma XI Graduate Student Paper Competition, The University of Tennessee, Knoxville, Tenn., Mar. 4, 1993.

Authors: C. Liu and J. R. Roth Title: Characteristics of a Steady-State, Low Power Glow Discharge at Atmospheric Pressure Publication: Bulletin of the American Physical Society Series II, vol. 37, No. 6, Nov., 1992.

Authors: J. Reece Roth, Mounir Laroussi and Chaoyu Liu Title: Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure Publication: 1992 19th IEEE International Conference on Plasma Science, Conference Record-Abstracts-1-3 Jun., 1992.

Author: Witold Rakowski Title: Effect and Cost of Plasma Treatment of Polypropylene Melt Blown Webs Publication: Second Annual TANDEC Conference. 13–16 Oct., 1992.

Authors: Von Engel, A.; Seeliger, R.; and Steenbeck, M. Title: On the Glow Discharge At High Pressure. Publication: *Ziet, fur Physik,* vol. 85 (1993) pp. 144–160. English language translation of above from original German.

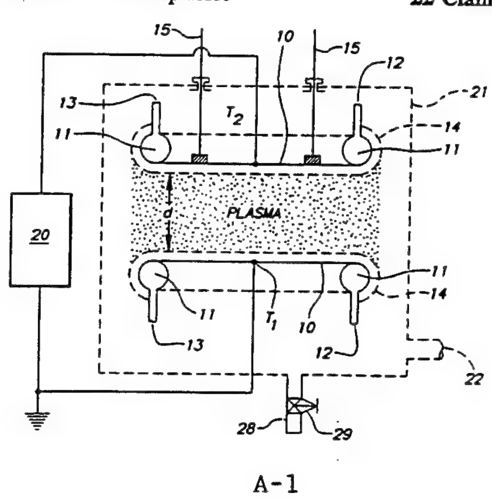
(List continued on next page.)

Primary Examiner—Robert J. Pascal
Assistant Examiner—Darius Gambino
Attorney, Agent, or Firm—Weiser & Associates

[57] ABSTRACT

A steady-state, glow discharge plasma is generated within the volume between a pair of parallel, insulated metal plate electrodes spaced up to 5 cm apart and R.F. energized with an rms potential of 1 to 5 KV at 1 to 100 KHz. The electrodes are located within an enclosure capable of maintaining an atmosphere other than atmospheric air between the electrode surfaces. Space between the electrodes is occupied by a noble gas such as helium, neon, argon, etc. or mixtures thereof.

22 Claims, 4 Drawing Sheets



OTHER PUBLICATIONS

EPO Publication No. 0,068,775 Issue Date: Jan. 5, 1983 Inventor: Hata, et al.

EPO Publication No. 0,117,561 Issue Date: Sep. 5, 1984 Inventor: Akagi, et al.

Authors: Wakida, T.; Kawamura, H.; Han L.: Hwan Kim, K.; Goto, T.; and Takagishi, T. Title: Changes In Surfaace Properties of Poly(ethylene terephthalate) Treated With Low Temperature Plasma: Effect of Pretreatment With Dimethylformamide Publication: *Sen-I-Gakkaishi,* vol. 42, No. 2 (1986).

Authors: Wakida, T.; Kawamura, H.; Song, J. C.; Goto, T.; Takagishi, T. Title: Surface Free Energy of Poly(ethylene Terepathalate) and Nylon 6 Films Treated With Low Temperature Plasma Publication: *Sen-I--Gakkaishi,* vol. 43, No. 7 (1987).

Japanese Patent No. 62-235,339 Issue Date: Oct. 15, 1987 Inventors: M. Kogoma et al.

Author: Rakowski, W. Title: Plasma Modification of Wool Under Industrial Conditions Publication: *Melliand Textilberichte,* vol. 70 (1989) pp. 780-785.

Authors: Roth, J. R.; Spence, P. D.; Liu, C. Title: Plasma-Related Characteristics of a Steady-State Glow Discharge at Atmospheric Pressure Publication: Paper 2P-18, *Proc. 1993 IEEE International Conference on Plasma Science,* Vancouver, B.C. IEEE Catalog No. 93-CH3334-0, ISBN 0-7803-1360-7 (1993), p. 129.

Authors: Roth J. R.; Spence, P. D.; Liu, C. Title: Preliminary Measurements of the Plasma Properties of a One Atmosphere Glow Discharge Plasma. Publication: Paper presented at *35th Annual Meeting of the APS Division of Plasma Physics,* St. Louis, Mo., Nov. 1-5, 1993; *APS Bulletin,* Series II, vol. 38, No. 10 (1993), p. 1901.

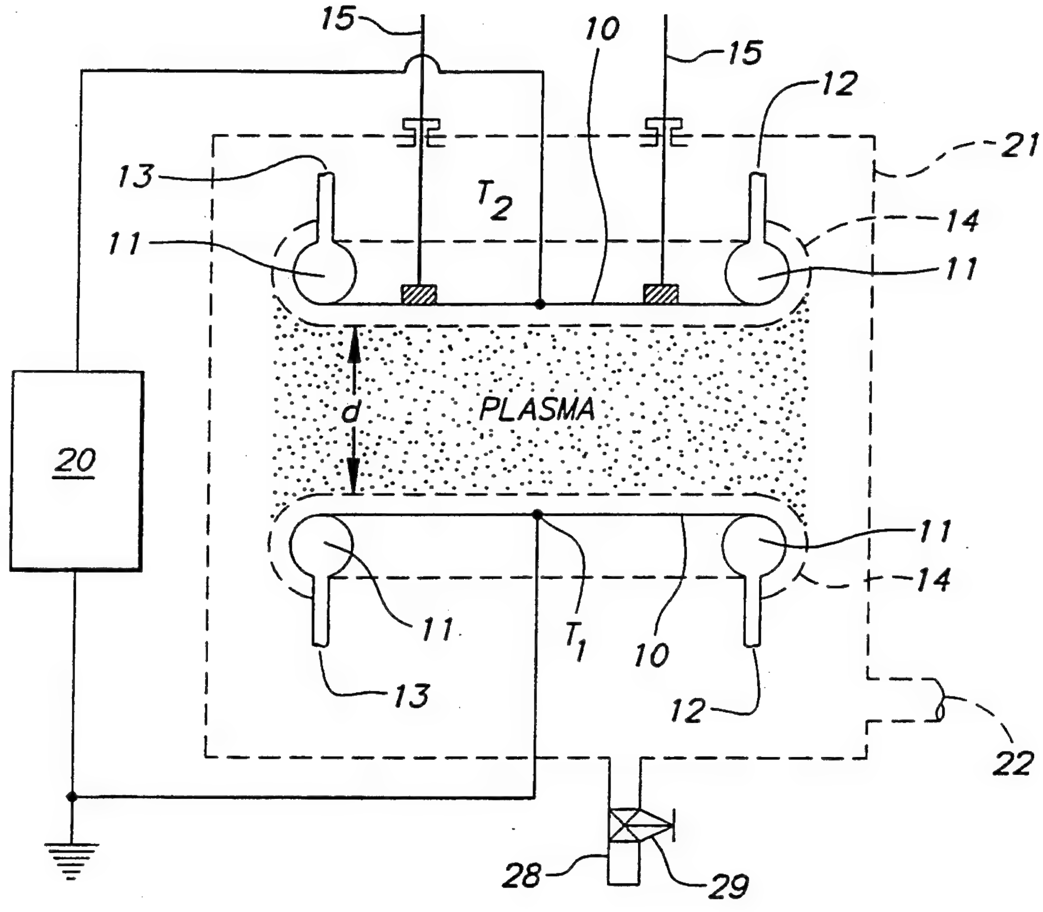


FIG. 1

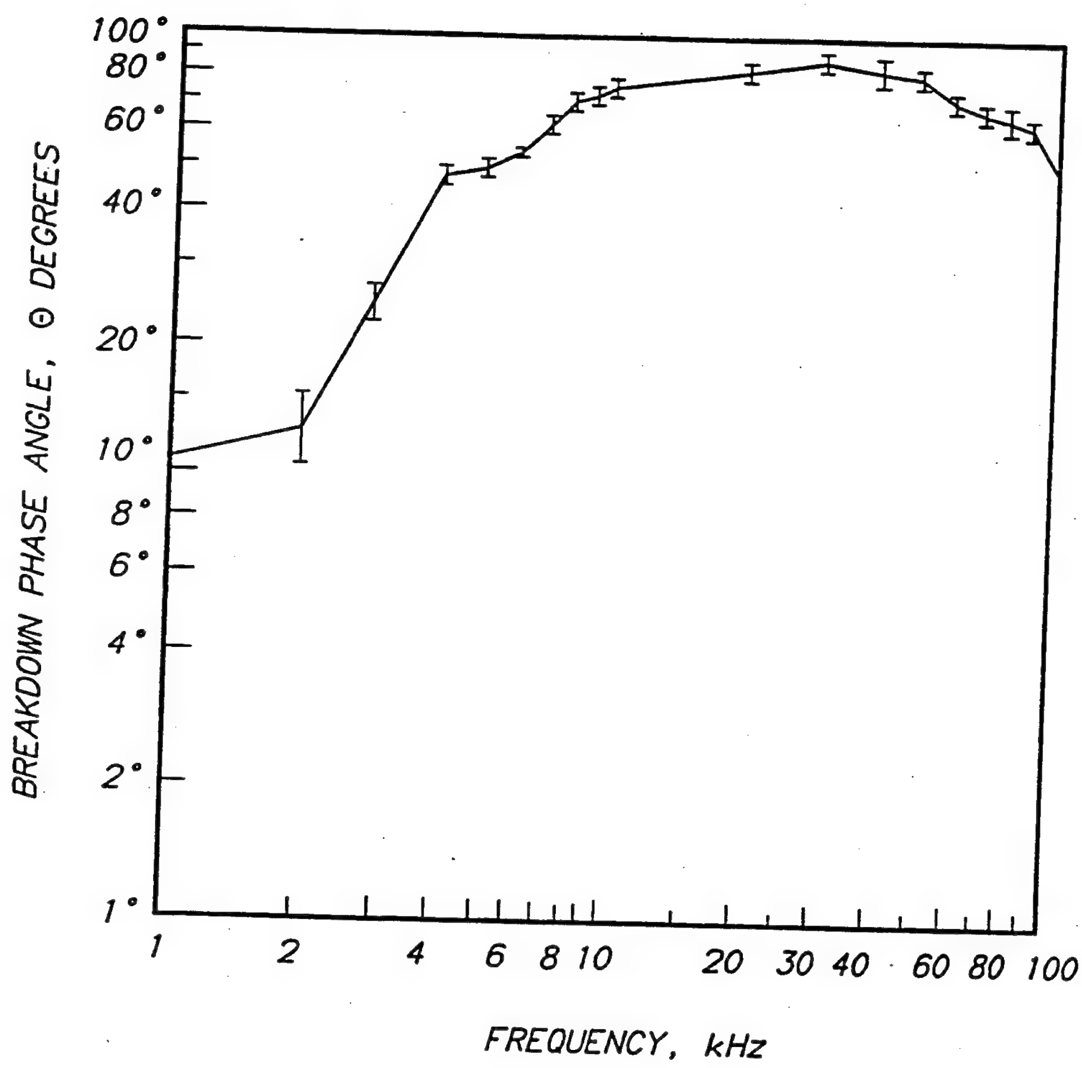

100°
80°
60°
40°
20°
10°
8°
6°
4°
2°
1°
BREAKDOWN PHASE ANGLE, Θ DEGREES
1
2
4
6
8
10
20
30
40
60
80
100
FREQUENCY, kHz

FIG. 2

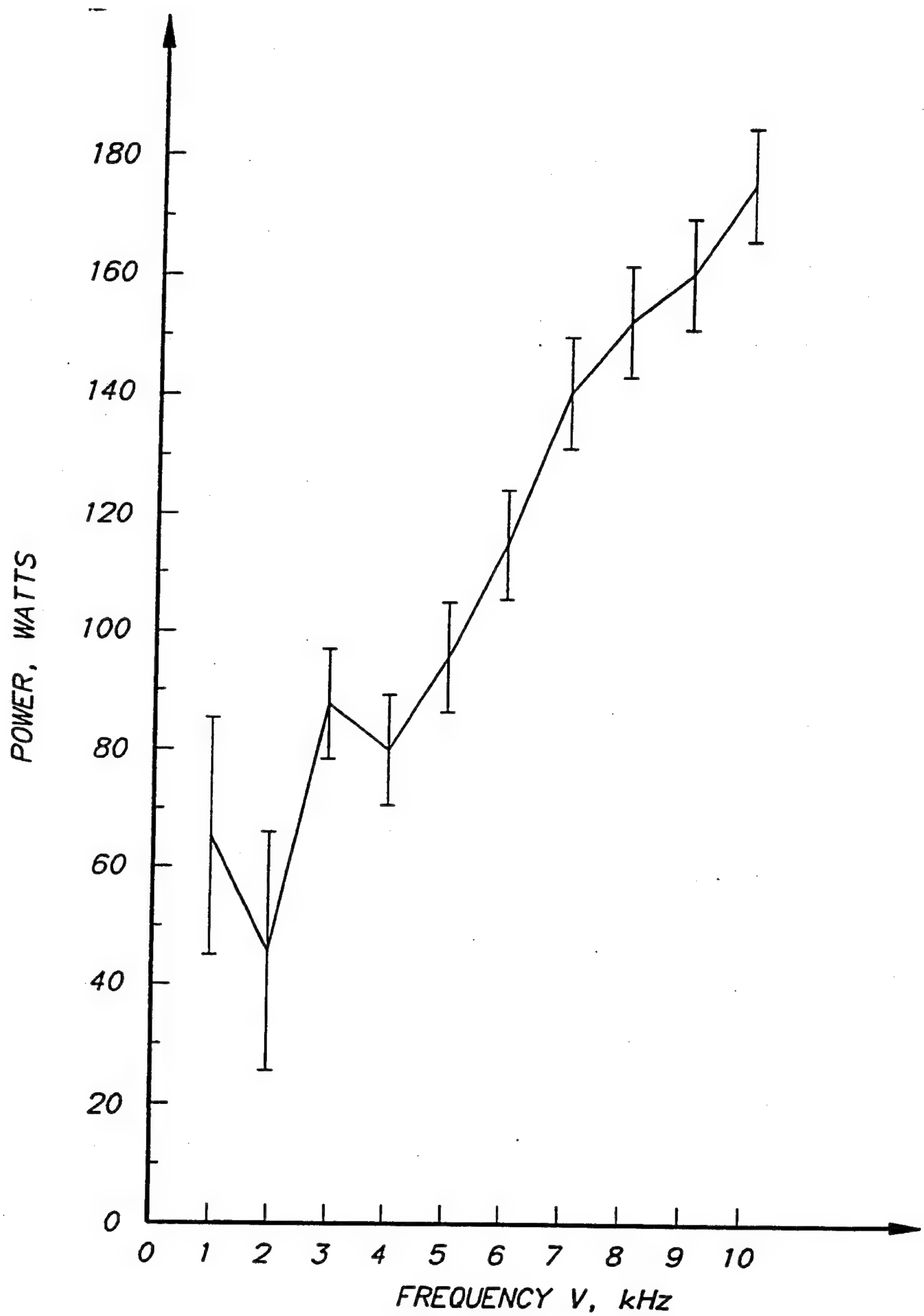

180
160
140
120
100
80
60
40
20
0
POWER, WATTS
0 1 2 3 4 5 6 7 8 9 10
FREQUENCY V, kHz

FIG. 3

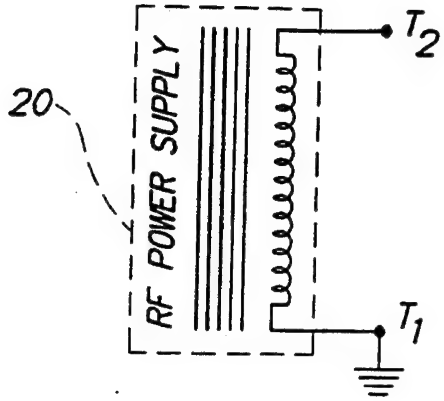


FIG. 4

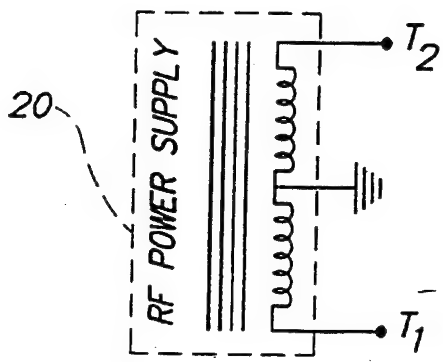


FIG. 5

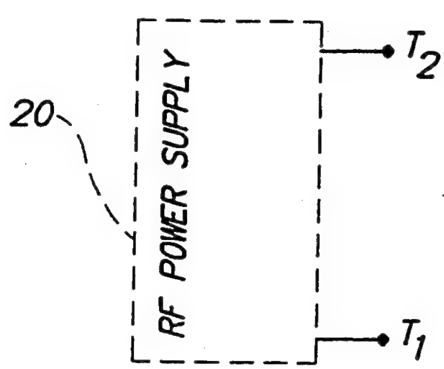


FIG. 6

STEADY-STATE, GLOW DISCHARGE PLASMA

LICENSE RIGHTS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of contract No. AFOSR 89-0319 awarded by The U.S. Air Force.

BACKGROUND OF THE INVENTION

1. Field of Invention

The present invention relates to methods and apparatus for generating low power density glow discharge plasmas at atmospheric pressure.

2. Description of the Prior Art

In the discipline of physics, the term "plasma" describes a partially ionized gas composed of ions, electrons and neutral species. This state of matter may be produced by the action of either very high temperatures, strong electric or radio frequency (R.F.) electromagnetic fields. High temperature or "hot" plasmas are represented by celestial light bodies, nuclear explosions and electric arcs. Glow discharge plasmas are produced by free electrons which are energized by an imposed direct current (DC) or R.F. electric fields and then collide with neutral molecules. These neutral molecule collisions transfer energy to the molecules and form a variety of active species including metastables, atomic species, free radicals and ions. These active species are chemically active and/or physically modify the surface of materials and may therefore serve as the basis of new chemical compounds and property modifications of existing compounds.

Low power plasmas known as dark discharge coronas have been widely used in the surface treatment of thermally sensitive materials such as paper, wool and synthetic polymers such as polyethylene, polypropylene, polyolefin, nylon and poly(ethylene terephthalate). Because of their relatively low energy content, corona discharge plasmas can alter the properties of a material surface without damaging the surface.

Glow discharge plasmas represent another type of low power density plasma useful for non-destructive material surface modification. These glow discharge plasmas can produce useful amounts of ultraviolet radiation. Glow discharge plasmas have the additional advantage therefore of producing UV radiation in the simultaneous presence of active species. However, glow discharge plasmas have heretofore been successfully generated typically in low pressure or partial vacuum environments below 10 torr, necessitating batch processing and the use of expensive vacuum systems.

It is, therefore, an object of the present invention to teach the construction and operating parameters of a glow discharge plasma operating at a gas pressure of about one atmosphere or slightly greater.

INVENTION SUMMARY

This and other objects of the invention to be subsequently explained or made apparent are accomplished with an apparatus based upon a pair of electrically insulated metallic plate electrodes. These plates are mounted in face-to-face parallel alignment with means for reciprocatory position adjustment up to at least 5 cm of separation. Preferably, the plates are water cooled and coated with a dielectric insulation.

A radio frequency power amplifier connected to both plates delivers up to several hundred watts of power at a working voltage of 1 to at least 5 KV rms and at 1 to 100 KHz.

At least in the volume between the plates wherein the glow discharge plasma is established, a one atmosphere charge of helium, argon or other noble gas is established and maintained.

BRIEF DESCRIPTION OF THE DRAWINGS

Relative to the drawings wherein like reference characters designate like or similar elements throughout the several figures of the drawings:

FIG. 1 is a schematic of the present invention component assembly.

FIG. 2 is a graph of amplifier frequency and corresponding breakdown current phase angles respective to a particular operating example of the invention.

FIG. 3 is a graph of amplifier frequency and corresponding power consumption respective to a particular operating example of the invention.

FIGS. 4, 5 and 6 represent alternative power supply circuits.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the invention schematic illustrated by FIG. 1, the electrodes **10** are fabricated of copper plate having a representative square plan dimension of 25 cm×25 cm. Silver soldered to the plates **10** are closed loops **11** of 1.9 cm copper tubing having hose nipples **12** and **13** connected therewith on opposite sides of the closed tubing loop. Not shown are fluid flow conduits connected to the inlet nipples **12** for delivering coolant fluid to the loop **11** and to the outlet nipples **13** for recovering such coolant fluid.

The integral metallic units comprising plates **10** and tubing **11** are covered with a high dielectric insulation material **14**.

Preferably, some mechanism should be provided for adjusting the distance d between plates **10** up to at least cm separation while maintaining relative parallelism. Such a mechanism is represented schematically in FIG. 1 by the rod adjusters **15** secured to the upper plate **10**. This arrangement anticipates a positionally fixed lower plate **10**.

Energizing the plates **10** is a low impedance, high voltage, R.F. power amplifier **20** having independently variable voltage and frequency capacities over the respective ranges of 1 to at least 5 KV and 1 to 100 KHz.

Surrounding the plate assembly is an environmental isolation barrier **21** such as a structural enclosure suitable for maintaining a controlled gas atmosphere in the projected plan volume between the plates **10**. Inlet port **22** is provided to receive an appropriate gas such as helium or argon, mixtures of either with air or a mixture of argon with helium. In any case, gas pressure within the isolation barrier **21** is substantially ambient thereby obviating or reducing the need for gas tight seals. Normally, it is sufficient to maintain a low flow rate of the modified atmosphere gas through the inlet port **22** that is sufficient to equal the leakage rate. Since the pressure within the isolation barrier **21** is essentially the same as that outside the barrier, no great pressure differential drives the leakage rate. A vent conduit **28** controlled by valve **29** is provided as an air escape channel during initial flushing of the enclosure. Thereafter, the valve **29** is closed for normal operation.

EXAMPLE 1

In a first operational example of the invention, the above described physical apparatus sustained a glow discharge plasma in one atmosphere of helium at standard temperature with a separation distance d of 3.0 cm between plates **10**. The plates were charged with a 4.4 KV working potential. Holding these parameters constant, the R.F. frequency was increased as an independent variable. As the dependent variable, FIG. **2** charts the corresponding breakdown current phase angle. Similarly, FIG. **3** charts the power required to sustain the plasma at the respective R.F. frequencies.

EXAMPLE 2

In a second operational example of the invention, the above described physical apparatus is used to sustain a glow discharge plasma in one atmosphere of helium at standard temperature with a separation distance d of 1.0 cm between plates **10**. In this example, the frequency was held constant at 30 KHz while plate potential was manipulated as the independent variable and current breakdown phase angle, Θ, (Table 1) and power, W, (Table 2) measured as dependent variables.

TABLE 1

V (KV)	1	1.5	2	2.5	3	3.5
Θ (deg)	28	40	61	46	65	76.5

TABLE 2

V (KV)	1	1.5	2	2.5	3	3.5
P (W)	7	13	22	57	50	44.9

EXAMPLE 3

A third operational example of the invention included a one atmosphere environment of helium between a 1 cm separation distance d between plate electrodes **10** charged at 1.5 KV rms potential. R.F. frequency was manipulated as the independent variable. As a measured dependent variable, Table 3 reports the corresponding phase angle Θ of breakdown current. The measured dependent variable of Table 4 reports the corresponding power consumption data.

TABLE 3

f (KHz)	10	20	30	40	50	60	70	80	90	100
Θ (deg)	43	32	43	52	54	61	60	56	45	22.5

TABLE 4

f (KHz)	10	20	30	40	50	60	70	80	90	100
P (W)	5	8	11	19	35	43	47	57	89	124

EXAMPLE 4

The largest volume helium plasma of 2.8 liters was achieved with the above described apparatus at a 4.5 cm plate separation having a 5 KV potential charged at 4 KHz.

It will be understood by those of ordinary skill in the art that the present invention is capable of numerous arrangements, modifications and substitutions of parts without departing from the scope of the invention. In particular, FIGS. **4** and **6** represent respective power supply options having respective attractions. FIG. **4** corresponds to the FIG. **1** illustration wherein the bottom electrode terminal T_1 is connected to ground potential and the top terminal T_2 is charged at the full working potential.

FIGS. **4**, **5** and **6** are electrical equivalents wherein the T_1 and T_2 voltages are 180° out of phase but at only half the maximum potential. FIG. **5** represents a grounded center tap transformer whereas FIG. **6** represents a solid state power circuit embodiment with or without a provision for a grounded center tap.

We claim:

1. Apparatus to generate and maintain a glow discharge plasma at a pressure of about 1 atmosphere, the apparatus comprising

a pair of electrically insulated plate electrodes aligned and secured in parallel facing position,

means for supplying and maintaining a noble gas at a pressure of about one atmosphere in the volumetric space between said plate electrodes, and

radio frequency amplifier means for generating and maintaining a glow discharge plasma by energizing said electrodes with a potential of 1 to at least 5 KV rms at 1 to 100 KHz.

2. An apparatus as described by claim **1** wherein the electrodes are spaced within 5 cm of each other.

3. An apparatus as described by claim **1** which comprises means for establishing and maintaining a gas barrier envelope surrounding said plates and the volumetric space therebetween.

4. An apparatus as described by claim **3** wherein said means for supplying and maintaining the gas comprises gas supply means to provide a substantially steady supply flow of said gas.

5. An apparatus as described by claim **1** wherein said gas is helium.

6. An apparatus as described by claim **1** wherein said gas is a mixture of helium and air.

7. An apparatus as described by claim **1** wherein said gas is argon.

8. An apparatus as described by claim **1** wherein said gas is a mixture of argon and air.

9. An apparatus as described by claim **1** wherein said gas is a mixture of argon and helium.

10. An apparatus as described by claim **1** wherein said plates are fluid cooled.

11. An apparatus as described by claim **10** wherein fluid flow conduits are bonded to said plates to extract heat from said plates.

12. A method of generating and maintaining a glow discharge plasma at a pressure of about 1 atmosphere within a volumetric space between two parallel plate electrodes energized by radio frequency amplifier means, said method comprising the steps of operating said amplifier means to energize said electrodes with a potential of 1 to at least 5 KV rms at 1 to 100 KHz frequency while charging and maintaining the volumetric space between said electrodes with a noble gas at approximately 1 atmosphere of pressure.

13. A method as described by claim **12** wherein said electrodes are enclosed by an environmental gas barrier internally charged by a substantially continuous flow of said gas.

14. A method as described by claim **13** wherein said gas is helium.

15. A method as described by claim **13** wherein said gas is a mixture of helium and air.

16. A method as described by claim **13** wherein said gas is argon.

17. A method as described by claim 13 wherein said gas is a mixture of argon and air.

18. A method as described by claim 13 wherein said gas is a mixture comprising helium and argon.

19. A method as described by claim 12 wherein said electrodes are positioned at a separation distance therebetween of 5 cm or less.

20. A method as described by claim 19 wherein at least one of said electrodes is positionally adjustable relative to the other.

21. A method as described by claim 12 wherein said amplifier frequency is variable over the range of 1 to 100 KHz.

22. A method as described by claim 12 wherein said amplifier potential is variable over the range of 1 to at least 5 KV rms.

* * * * *

US005403453A

United States Patent [19]

Roth et al.

[11] Patent Number: 5,403,453

[45] Date of Patent: Apr. 4, 1995

[54] METHOD AND APPARATUS FOR GLOW DISCHARGE PLASMA TREATMENT OF POLYMER MATERIALS AT ATMOSPHERIC PRESSURE

[75] Inventors: John R. Roth; Peter P. Tsai; Larry C. Wadsworth; Chaoya Liu; Paul D. Spence, all of Knoxville, Tenn.

[73] Assignee: The University of Tennessee Research Corporation, Knoxville, Tenn.

[21] Appl. No.: 145,349

[22] Filed: Oct. 29, 1993

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 68,739, May 28, 1993.

[51] Int. Cl.6 .... H05F 3/00
[52] U.S. Cl. 204/164
[58] Field of Search 204/164

[56] References Cited

FOREIGN PATENT DOCUMENTS

0068775 1/1983 European Pat. Off. .
0117561 9/1984 European Pat. Off. .
200133 9/1986 Japan .
62-235339 10/1987 Japan .

OTHER PUBLICATIONS

Authors: Von Engel, A.; Seeliger, R.; & Steenbeck, M. Title: On the Glow Discharge at High Pressure Publication: *Ziet, fur Physik*, vol. 85 (1933) pp. 144–160.
Authors: Wakida, T.; Kawamura, H.; Han, L.; Hwan Kim, K.; Goto, T.; & Takagishi, T. Title: Changes in Surface Properties of Poly(Ethylene Terephthalate) Treated with Low Temperature Plasma: Effect of Pretreatment with Dimethylformamide Publication: *sen-i gakkaishi*, vol. 43, No. 7 (1987).
Authors: Wakida, T.; Kawamura, H.; Song, J. C.; Goto, T.; Takagishi, T. Title: Surface Free Energy Poly-(Ethylene Terephthalate) and Nylon 6 Films Treated with Low Temperature Plasma Publication: *Seni-I Gakkaishi*, vol. 43, No. 7 (1987).
Authors: Kogoma, M.; Kasai, H.; Takahashi, K.; Moriwaki, T. & Okazaki, S. Title: Wettability Control of a Plastic Surface by CF_4 Plasma and Its Etching Effect Publication: *J. Phys. D: Appl. Phys.*, vol. 20 (1987).
Authors: Kanazawa, S.; Kogoma, M.; Moriwaki, T.; & Okazaki, S. Title: Stable Glow Plasma at Atmospheric Pressure Publication: *J. Physics D: Appl. Phys.*, vol. 21 (1988) pp. 838–840.
Author: Rakowski, W. Title: Plasma Modification of Wool Under Industrial Conditions Publication: *Melliand Textilberichte*, vol. 70 (1989) pp. 780–785.
Authors: Yokoyama, T.; Kogoma, M.; Moriwaki, T.; & Okazaki, S. Title: The Mechanism of the Stabilisation of Glow Plasma at Atmospheric Pressure Publication: *J. Physics D. App. Phys.*, vol. 23 (1990) pp. 1125–1128.
Authors: Naoki Kanda; Masuhiro Kogoma; Hiroshi Jinno; Hiroshi Uchiyama & Sachiko Okazaki Title: Atmospheric Pressure Glow Plasma and Its Application to Surface Treatment and Film Deposition. Publication: *International Symposium on Plasma Chemistry*, Symposium Proceedings, vol. 3, Bochum, Germany, Aug. 4–9, 1991.
Authors: Liu, C.; Chen, D.; & Roth, J. R. Title: Characteristics of a Steady-State, Low Power Glow Discharge at Atmospheric Pressure Publication: *APS Bulletin*, vol. 37, No. 6 (1992) p. 1563.
Authors: Roth, J. R.; Liu, C.; & Laroussi, M. Title: Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure Publication: Paper

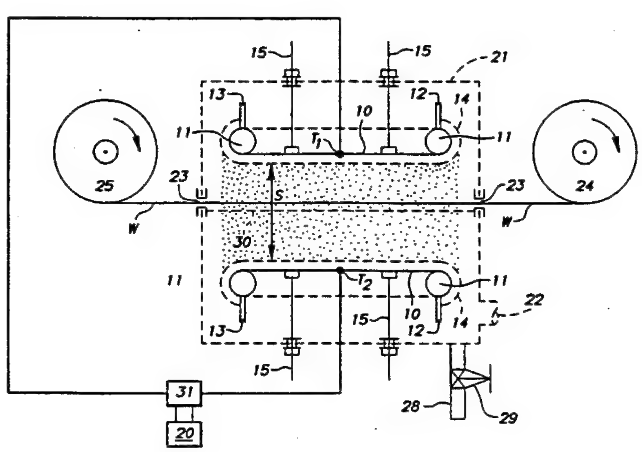
(List continued on next page.)

Primary Examiner—John Niebling
Assistant Examiner—Kishor Mayekar
Attorney, Agent, or Firm—Weiser & Associates

[57] ABSTRACT

Polymer materials such as film and fabrics, woven, non-woven and meltblown, may be non-destructively surface treated to improve water wettability, wickability, and other characteristics by exposure to a glow discharge plasma sustained at substantially atmospheric pressure in air or modified gas atmospheres comprising helium or argon.

12 Claims, 11 Drawing Sheets



OTHER PUBLICATIONS

5P–21, *Proc. 1992 IEEE International Conference on Plasma Science*, Tampa, Fla., IEEE Catalog No. 92–TH0460–6, ISBN 0–7803 0716–X (1992), pp. 170–171.

Authors: Reitz, H.; Schwarz, R.; Salge, J. G. H. Title: Power Modulation for Dielectric Barrier–Discharges Publication: Paper presented at *Twentieth Power Modulator Symposium*, 1992.

Author: Rakowski, W. Title: Effect and Cost of Plasma Treatment of Polypropylene Melt Blown Webs Publication: *Second Annual TANDEC Conference*, 13–16 Oct., 1992.

Author: Liu, C. Title: Plasma–Related Characteristics of a Steady–State Glow Discharge at Atmospheric Pressure Publication: Presented at the 1993 Sigma XI Graduate Student Paper Competition, The University of Tennessee, Knoxville, Tenn. on Mar. 4, 1993.

Authors: Roth, J. R.; Spence, P. D.; Liu, C. Title: Plasma–Related Characteristics of a Steady–State Glow Discharge at Atmospheric Pressure Publication: Paper 2P–18, *Proc. 1993 IEEE International Conference on Plasma Science*, Vancouver, B. C. IEEE Catalog No. 93–CH3334–0, ISBN 0–7803–1360–7 (1993), p. 129.

Authors: Roth, J. R.; Spence, P. D.; Liu, C. Title: Preliminary Measurements of the Plasma Properties of a One Atmosphere Glow Discharge Plasma Publication: Paper present at 35th Annual Meeting of the APS Division of Plasma Physics, St. Louis, Mo., Nov. 1–5, 1993; *APS Bulletin*, Series II, vol. 38, No. 10 (1993), p. 1901.

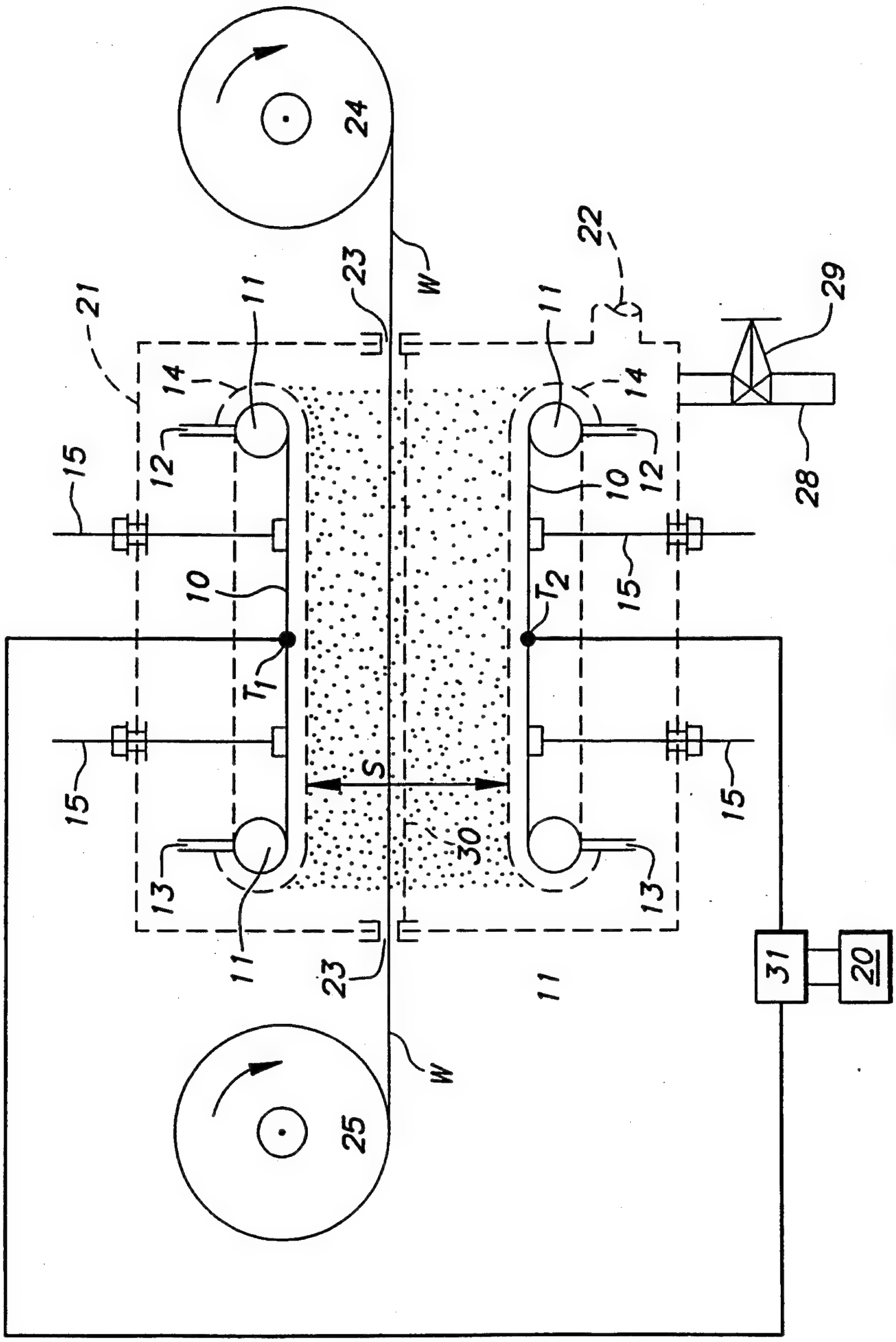
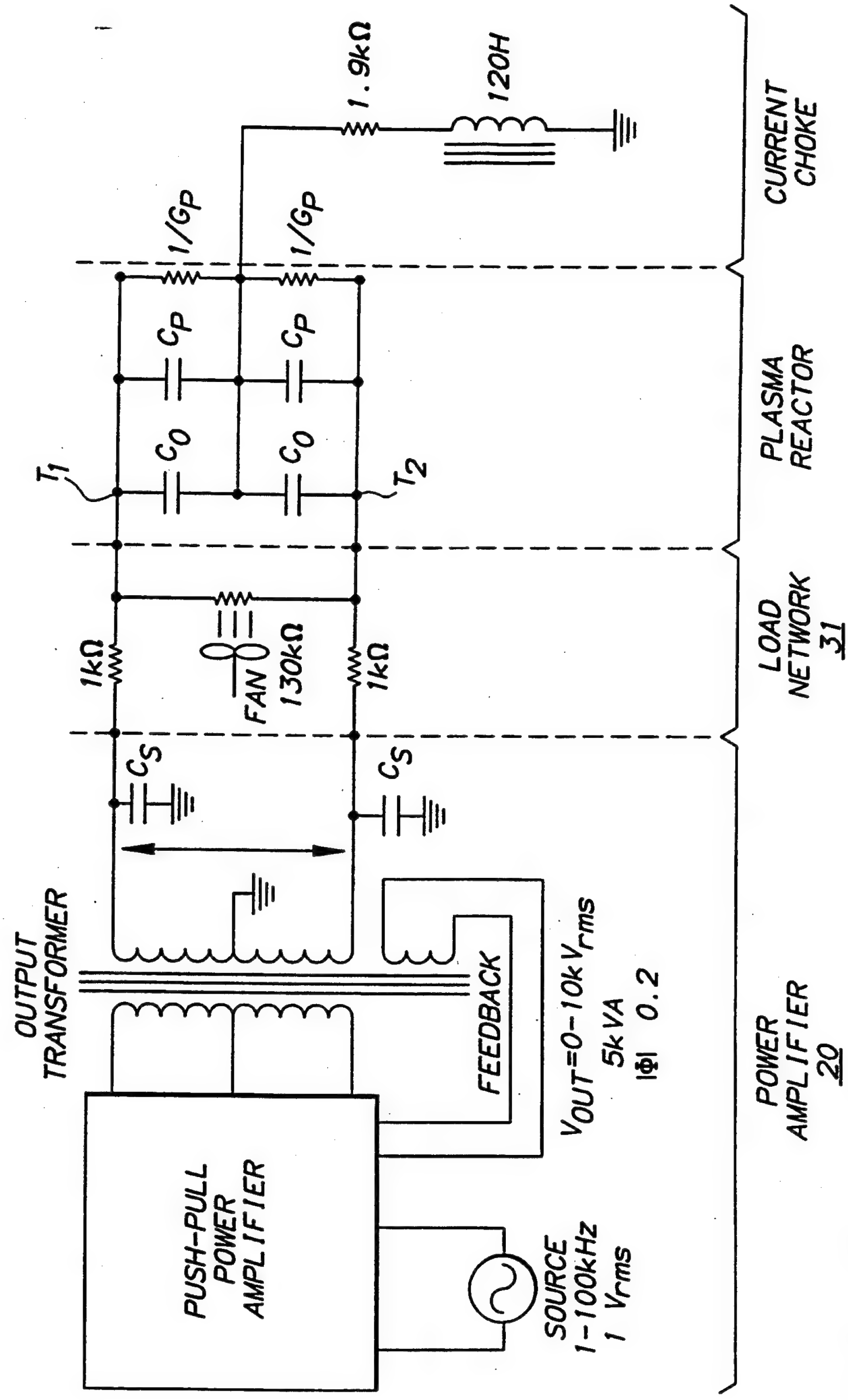

24
25
W
W
23
23
21
22
29
28
11
11
11
11
11
14
14
12
12
15
15
15
15
10
10
T1
T2
S
30
13
13
31
20

FIG. 1



1.9kΩ
120H
CURRENT CHOKE
1/G_P
1/G_P
C_P
C_P
C_O
C_O
T_1
T_2
PLASMA REACTOR
1kΩ
FAN
130kΩ
1kΩ
LOAD NETWORK 31
C_S
C_S
OUTPUT TRANSFORMER
FEEDBACK
V_{OUT}=0-10k V_{rms}
5k VA
1Φ 0.2
POWER AMPLIFIER 20
PUSH-PULL POWER AMPLIFIER
SOURCE 1-100kHz 1 V_{rms}

FIG. 2

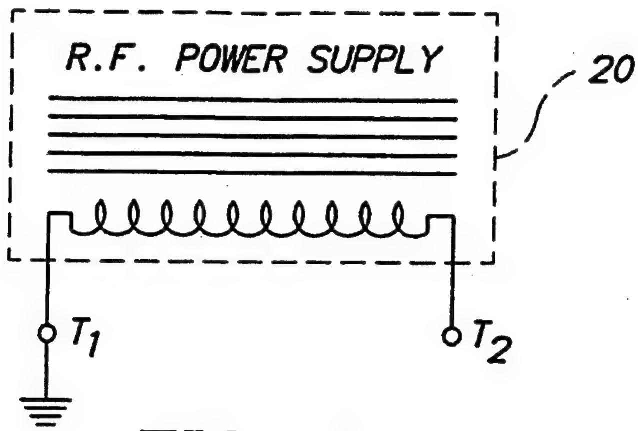


FIG. 3

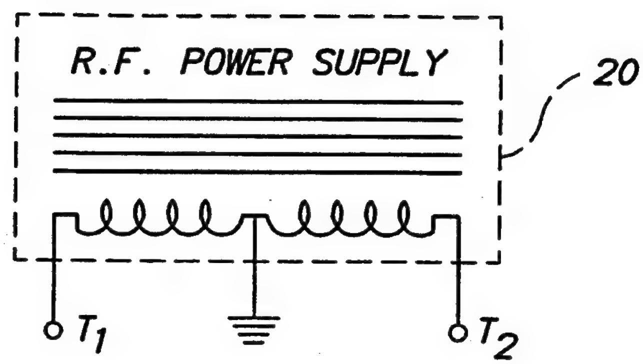


FIG. 4

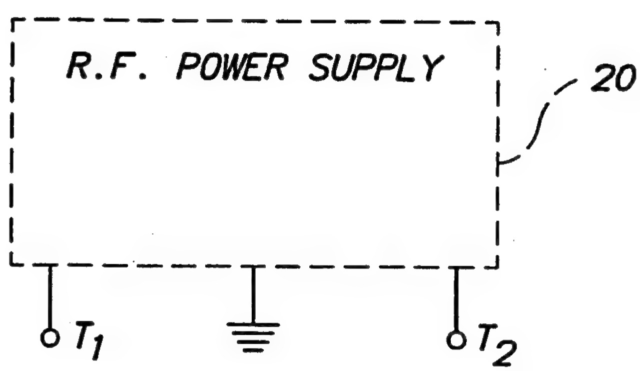


FIG. 5

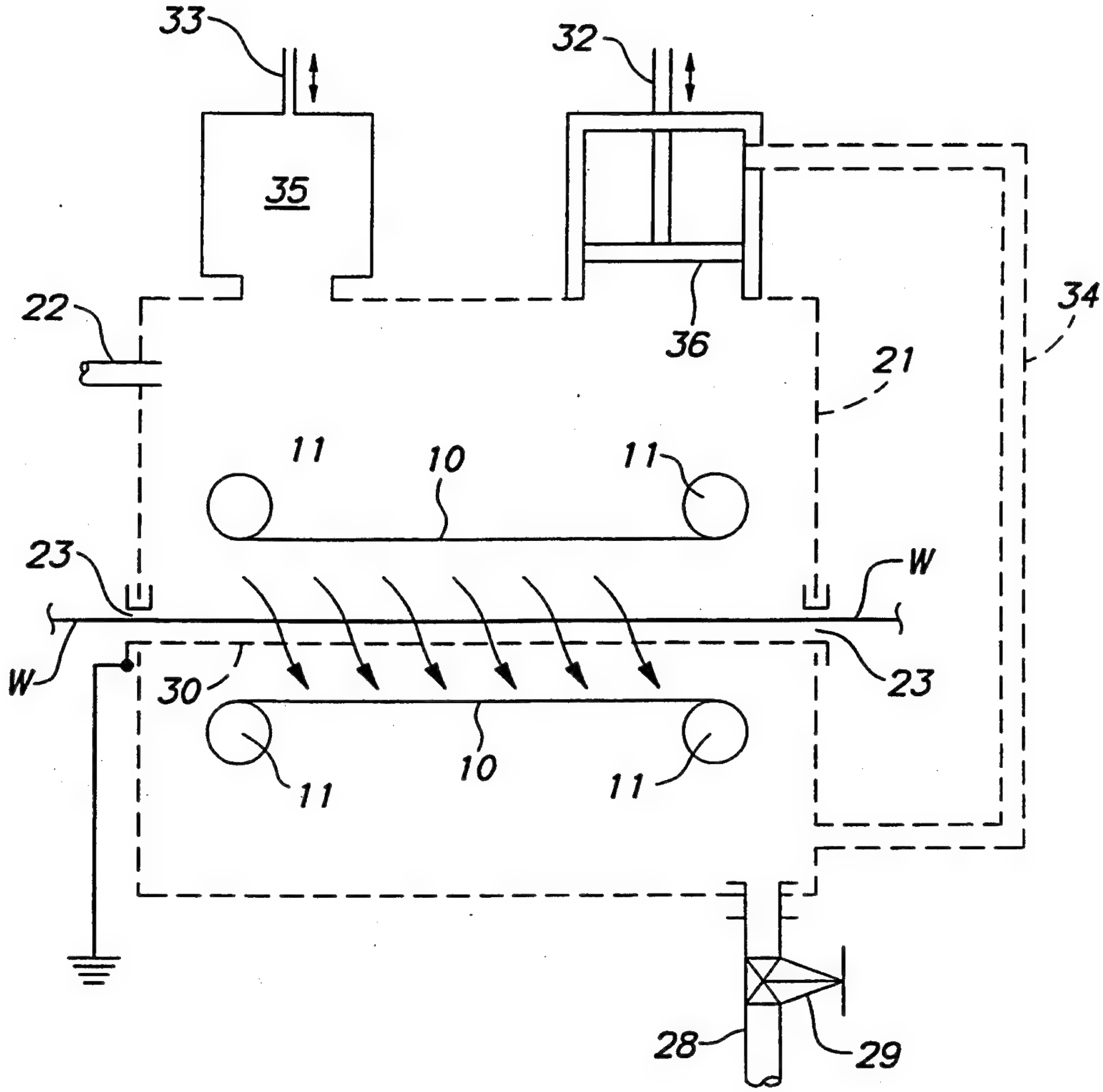


FIG. 6

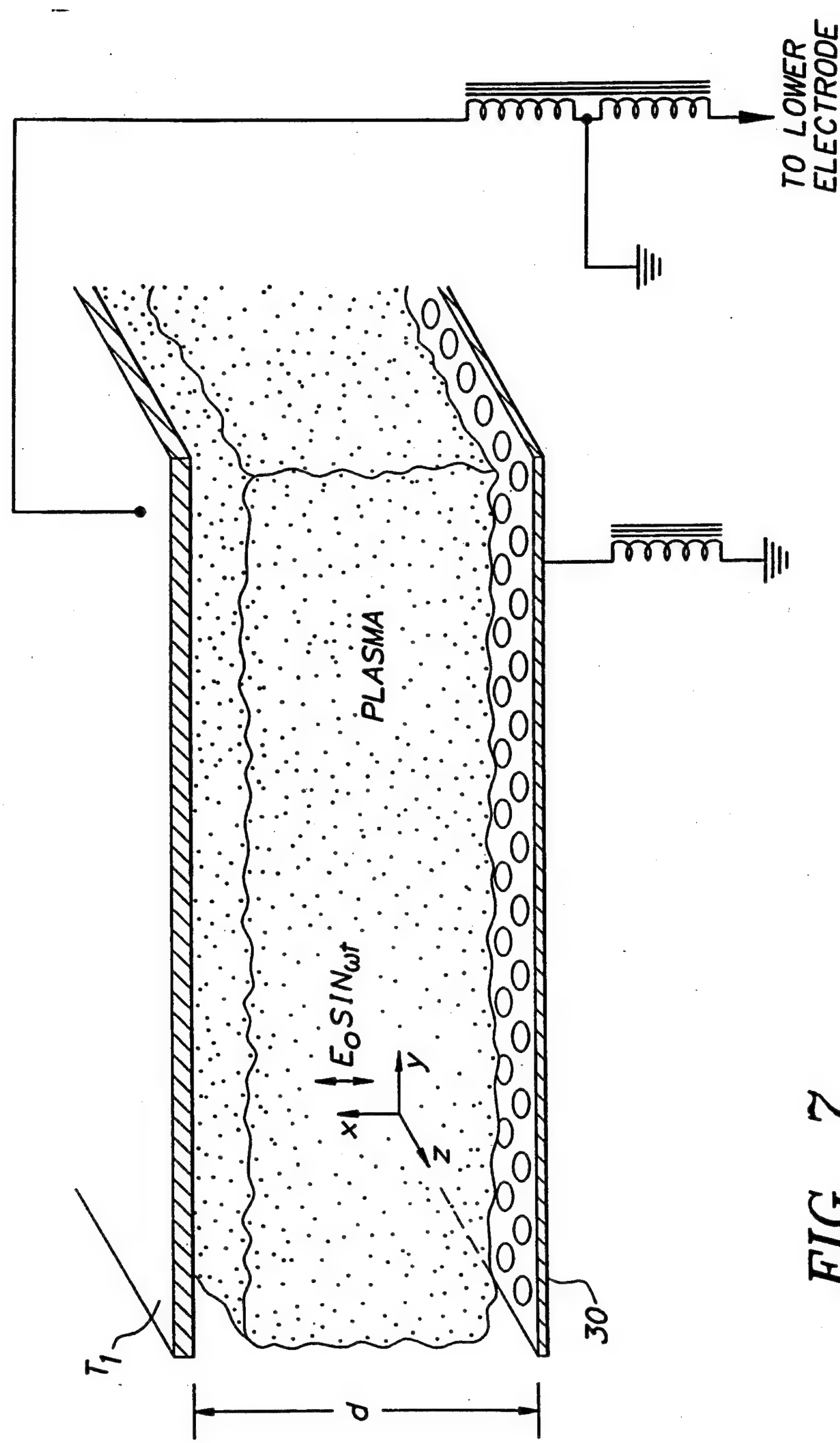


FIG. 7

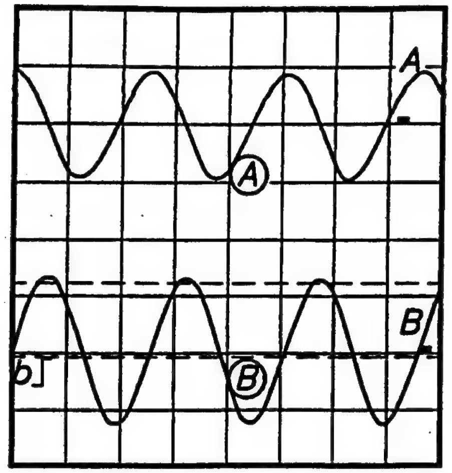


FIG. 8A

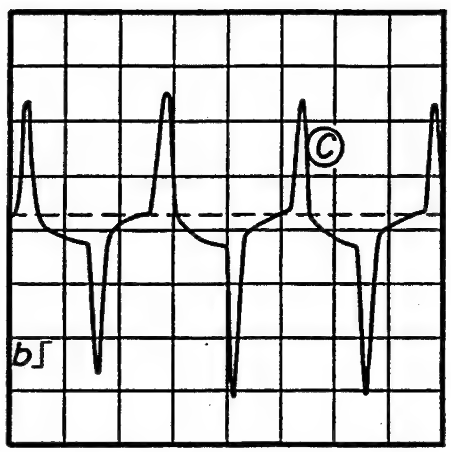


FIG. 8B

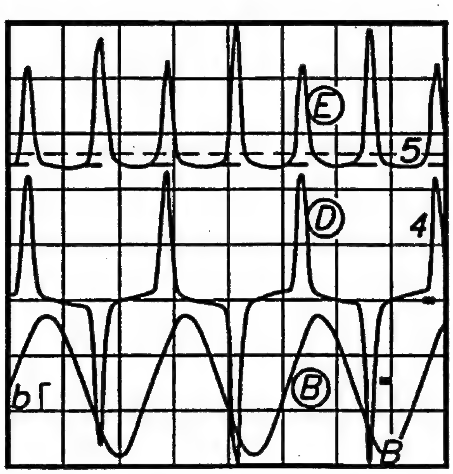


FIG. 8C

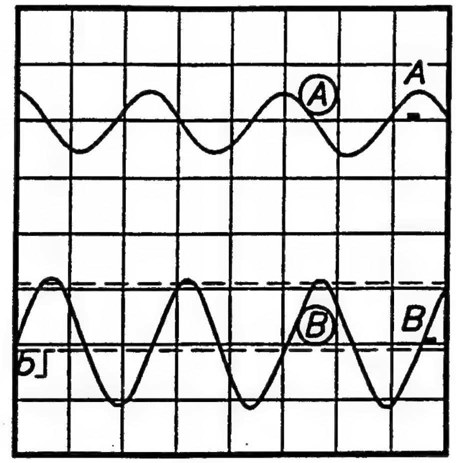


FIG. 9A

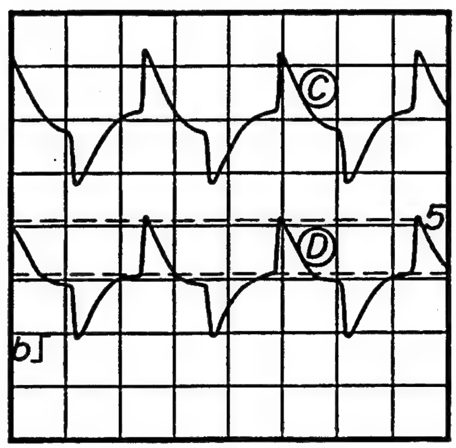


FIG. 9B

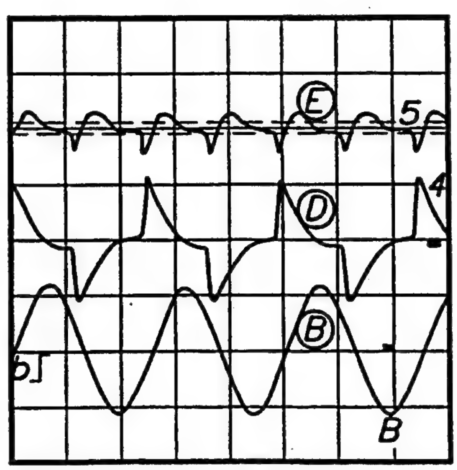
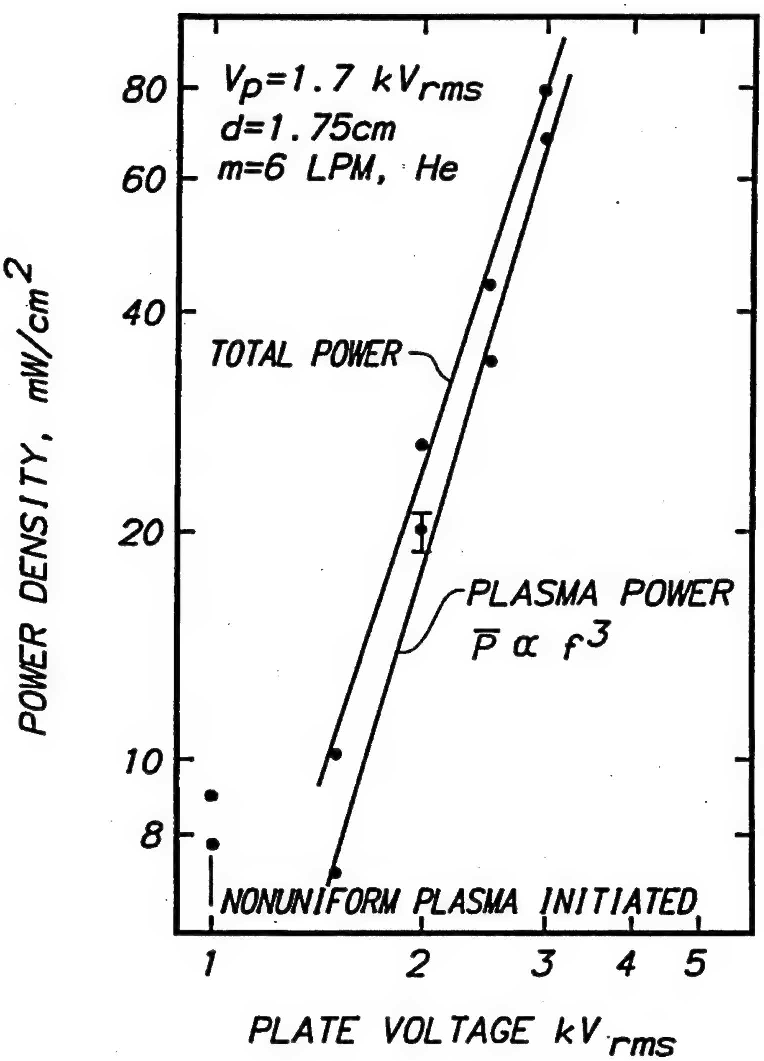
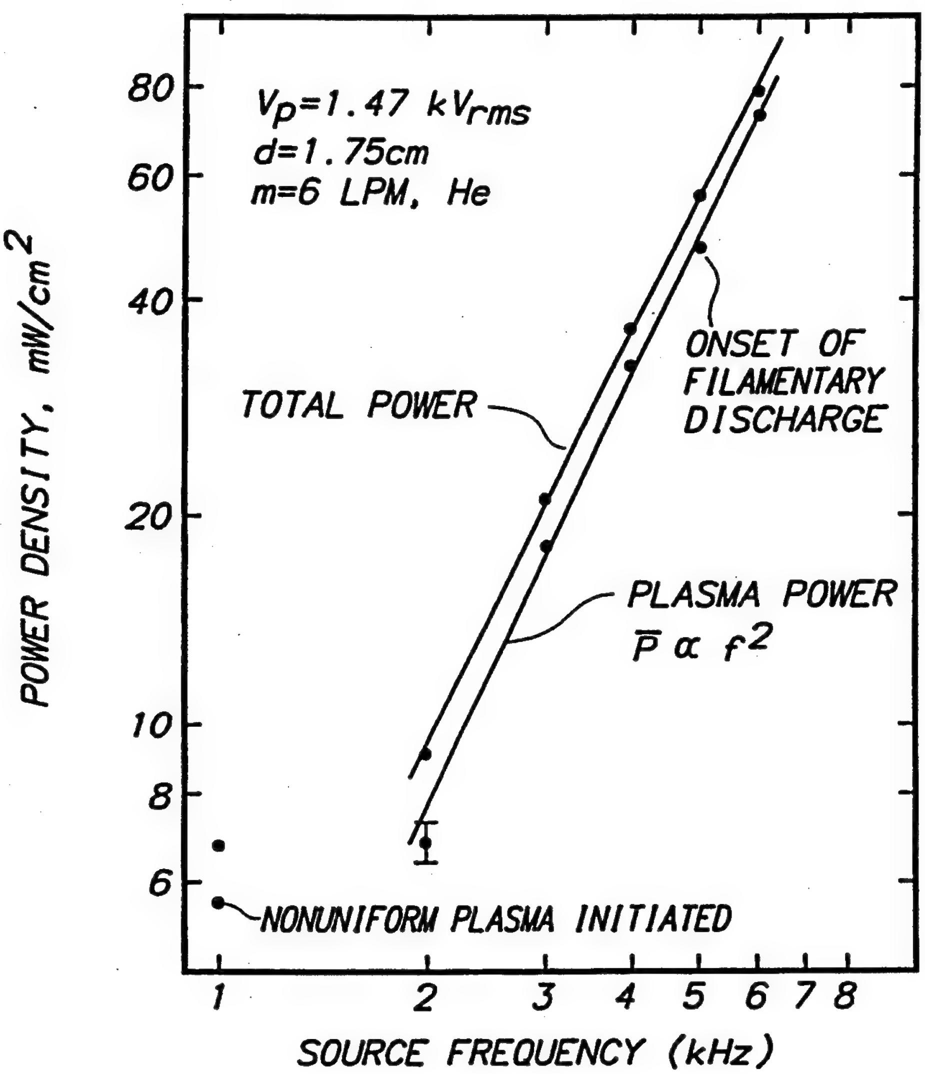


FIG. 9C



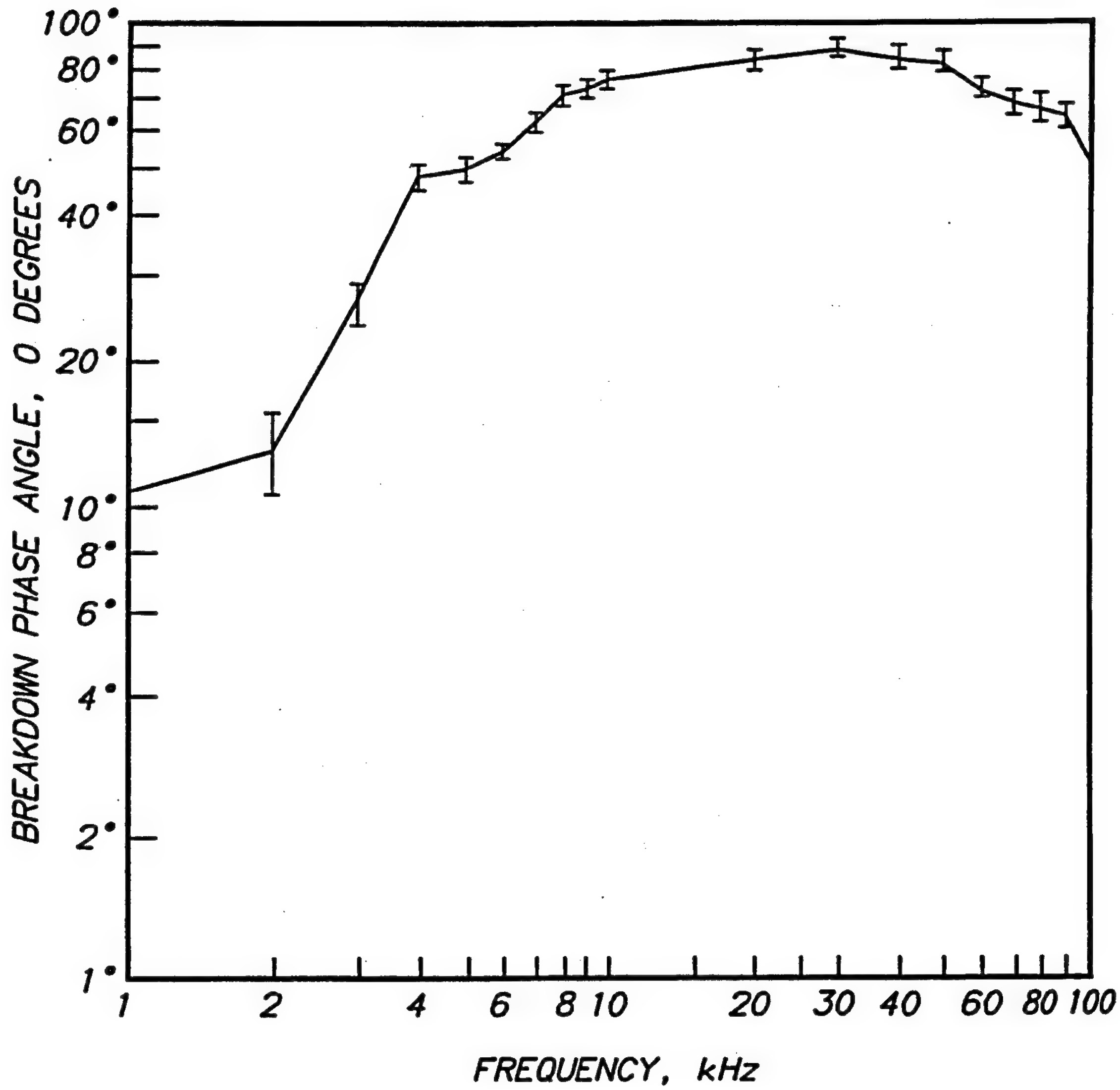
V_p=1.7 kV_{rms}
d=1.75cm
m=6 LPM, He
80
60
40
20
10
8
TOTAL POWER
PLASMA POWER
$\overline{P} \propto f^3$
NONUNIFORM PLASMA INITIATED
POWER DENSITY, mW/cm^2
1
2
3
4
5
PLATE VOLTAGE kV_{rms}

FIG. 10



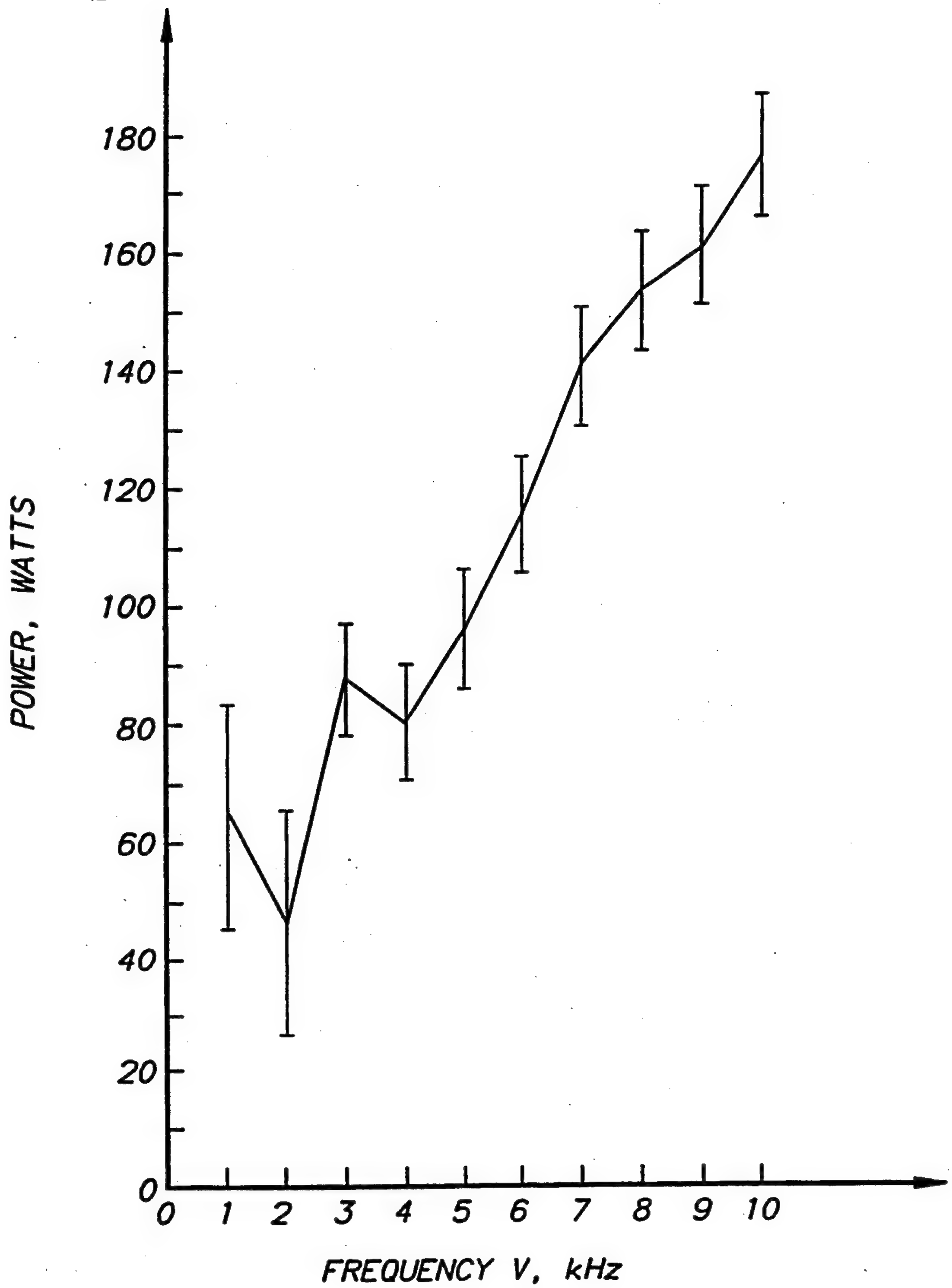
Vp=1.47 kVrms
d=1.75cm
m=6 LPM, He
80
60
40
20
10
8
6
POWER DENSITY, mW/cm2
TOTAL POWER
ONSET OF FILAMENTARY DISCHARGE
PLASMA POWER
P̄ α f2
NONUNIFORM PLASMA INITIATED
1
2
3
4
5
6
7
8
SOURCE FREQUENCY (kHz)

FIG. 11



100°
80°
60°
40°
20°
10°
8°
6°
4°
2°
1°
BREAKDOWN PHASE ANGLE, Θ DEGREES
1
2
4
6
8 10
20
30 40
60 80 100
FREQUENCY, kHz

FIG. 12



POWER, WATTS
180
160
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY V, kHz

FIG. 13

METHOD AND APPARATUS FOR GLOW DISCHARGE PLASMA TREATMENT OF POLYMER MATERIALS AT ATMOSPHERIC PRESSURE

This invention was made with government support under Contract No. AFOSR-89-0319 awarded by the U.S. Air Force. The government has certain rights in this invention.

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a Continuation-In-Part of U.S. patent application Ser. No. 08/068,739, filed May 28, 1993.

FIELD OF INVENTION

The present invention relates to a method and apparatus for modifying the surface properties of organic and inorganic polymer materials such as film and fabric, woven and non-woven.

DESCRIPTION OF THE PRIOR ART

One of the many utilities for meltblown polymer web is as a wet cell battery plate separator. The base polymer compound is impervious to the electrolyte. The meltblown, non-woven fabric structure is ion permeable if the surface thereof is thoroughly wetted by the electrolyte. Unfortunately, this latter requirement of wettability is not an inherent characteristic of most commercial polymers such as nylon, polypropylene, polyethylene and poly(ethylene terephthalate).

Although meltblown webs of these polymers are currently used as battery plate separators, wettability is achieved chemically by means of surfactants. This process not only generates hazardous industrial waste but produces a product of limited utility life.

Wettability is also a desirable property for tissue and cloth used to wipe or clean the body, for surgical sponges, wound dressings, feminine hygiene products and reuseable woven knit fabrics. Similarly, wettability is an important material surface property for printing and laminating.

Some success has been recently achieved by a glow discharge plasma treatment of polymer webs. The term "plasma" usually describes a partially ionized gas composed of ions, electrons and neutral species. This state of matter may be produced by the action of either very high temperatures, or strong direct current (DC) or radio frequency (RF) electric fields. High temperature or "hot" plasmas are represented by celestial light bodies, nuclear explosions and electric arcs. Glow discharge plasmas are produced by free electrons which are energized by an imposed DC or RF electric field and then collide with neutral molecules. These neutral molecule collisions transfer energy to the molecules and form a variety of active species which may include photons, metastables, individual atoms, free radicals, molecular fragments, monomers, electrons and ions. These active species are chemically active and/or capable of physically modifying the surface and may therefore serve as the basis of new surface properties of chemical compounds and property modifications of existing compounds.

Low power plasmas known as dark discharge coronas have been widely used in the surface treatment of thermally sensitive materials such as paper, wool and synthetic polymers such as polyethylene, polypropylene, polyolefin, nylon and poly(ethylene terephthalate). Because of their relatively low energy content, corona discharge plasmas can alter the properties of a material surface without damaging the surface.

Glow discharge plasmas represent another type of relatively low power density plasma useful for non-destructive material surface modification. These glow discharge plasmas can produce useful amounts of visible ultraviolet radiation. Glow discharge plasmas have the additional advantage therefore of producing visible and UV radiation in the simultaneous presence of active species. However, glow discharge plasmas have heretofore been successfully generated typically in low pressure or partial vacuum environments below 10 torr. Several polymer species exposed to low pressure glow discharge plasmas respond with enhanced surface wettability characteristics. However, the chemical/physical mechanisms are not understood and the characteristic is lost upon drying. Rewettability remains elusive.

The generation of low power density plasmas at one atmosphere is not new. Filamentary discharges between parallel plates in air at one atmosphere have been used in Europe to generate ozone in large quantities for the treatment of public water supplies since the late 19th century. Such filamentary discharges, while useful for ozone production, are of limited utility for the surface treatment of materials, since the plasma filaments tend to puncture or treat the surface unevenly.

It is an object of the present invention, therefore, to provide a non-byproduct producing process for enhancing the wettability of meltblown polymer webs and other types of polymeric substrates.

Another object of the invention is to teach a glow discharge plasma process for treating polymer web or film that provides a stable, rewettable product.

Another object of the invention is to provide a method and apparatus for continuously processing a polymer web or film of indefinite length through a glow discharge plasma at atmospheric pressure and standard temperature.

A still further object of the present invention to teach the construction and operating parameters of a glow discharge plasma having operability in an environmental pressure of about one atmosphere or slightly greater.

INVENTION SUMMARY

These and other objects of the invention to be subsequently explained or made apparent are accomplished with an apparatus based upon a pair of electrically insulated metallic plate electrodes which may or may not have a median plate or screen between them. These plates are mounted in face-to-face parallel or uniformly spaced alignment with means for reciprocatory position adjustment up to about 5 cm of separation. Preferably, the plates are water cooled and covered with a dielectric insulation.

A radio frequency power amplifier connected to both plates delivers at least 180 watts of reactive and plasma power at a working voltage of 1 to at least 5 KV rms and at 1 to 100 KHz.

An electric field established between the metallic plate electrodes must be strong enough to electrically break down the gas used, and is much lower for helium and argon than for atmospheric air. The RF frequency must be in the right range, discussed below, since if it is too low, the discharge will not initiate, and if it is too high, the plasma forms filamentary discharges between

the plates. Only in a relatively limited frequency band will the atmospheric glow discharge plasma reactor form a uniform plasma without filamentary discharges.

At least in the volume between the plates wherein the plasma is established, a one atmosphere charge of air, nitrous oxide, helium or argon is established and maintained for processing material such as polymer film and web to produce desired surface characteristics such as wettability and re-wettability.

BRIEF DESCRIPTION OF THE DRAWINGS

Relative to the drawings wherein like reference characters designate like or similar elements throughout the several figures of the drawings:

FIG. 1 is a schematic of the present invention component assembly.

FIG. 2 is an impedance matching network distinctively suitable for powering the present invention.

FIG. 3, 4 and 5 are representative alternative power supply output stage circuits.

FIG. 6 schematically represents an alternative embodiment of the invention.

FIG. 7 schematically represents the upper chamber of a one atmosphere glow discharge plasma reactor having a median grid plate.

FIG. 8 represents a graph of voltage, current and power waveforms for a uniform glow discharge plasma.

FIG. 9 represents a graph of voltage, current and power waveforms for a filamentary discharge plasma.

FIG. 10 is a log-log graph of total and plasma power density in milliwatts per cubic centimeter, as functions of RMS voltage applied to the electrodes.

FIG. 11 is a log-log graph of total and plasma power density in milliwatts per cubic centimeter, as functions of R. F. frequency.

FIG. 12 is a graph of amplifier frequency and corresponding breakdown current phase angles respective to a particular operating example of the invention.

FIG. 13 is a graph of amplifier frequency and corresponding power consumption respective to a particular operating example of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the invention schematic illustrated by FIG. 1, the electrodes **10** are fabricated of copper plate having a representative square plan dimension of 21.6 cm×21.6 cm. Silver soldered to the plates **10** are closed loops **11** of 0.95 cm copper tubing having hose nipples **12** and **13** connected therewith on opposite sides of the closed tubing loop. Not shown are fluid flow conduits connected to the inlet nipples **12** for delivering coolant fluid to the loop **11** and to the outlet nipples **13** for recovering such coolant fluid.

The integral metallic units comprising plates **10** and tubing **11** are covered with a high dielectric insulation material **14**.

Preferably, some mechanism should be provided for adjusting the distance s between plates **10** up to about 5 cm separation while maintaining relative parallelism. Such a mechanism is represented schematically in FIG. 1 by the rod adjusters **15** secured to the upper and lower plates **10**. This arrangement anticipates a positionally fixed median plate **30**.

Although parallelism is used in the context of parallel planes, it should be understood that the terms also comprises non-planar surfaces that are substantially equidistant. Also included are the geometry characteristics of a cylinder having an axis parallel to another cylinder or to a plate.

Energizing the plates **10** is a low impedance, high voltage, R. F. power amplifier **20** having independently variable voltage and frequency capacities over the respective ranges of 1 to at least 5 KV and 1 to 100 KHz. Between the RF power supply **20** and the plates **10** may be an impedance matching network **31**, described in greater detail relative to FIG. 2.

Surrounding the plate assembly is an environmental isolation barrier **21** such as a structural enclosure suitable for maintaining a controlled gas atmosphere in the projected plan volume between the plates **10**. Inlet port **22** is provided to receive an appropriate gas such as air, helium or argon, mixtures of helium or argon with oxygen or air or a mixture of argon with helium. In any case, gas pressure within the isolation barrier **21** is substantially ambient thereby obviating or reducing the need for gas tight seals. Normally, it is sufficient to maintain a low flow rate of the modified atmospheric pressure gas through the inlet port **22** that is sufficient to equal the leakage rate. Since the pressure within the isolation barrier **21** is essentially the same as that outside the barrier, no great pressure differential drives the leakage rate. A vent conduit **28** controlled by valve **29** is provided as an air escape channel during initial flushing of the enclosure. Thereafter, the valve **29** may be closed for normal operation.

Narrow material flow slits **23** are provided in the isolation barrier **21** to accommodate passage of a material web W between the plates **10** as drawn from a supply reel **24** onto a rewind reel **25**. Drive for the reels **24** and **25** is controlled to provide a predetermined residence time between the plates **10** and within the plasma for any given web element.

To broaden the range of operating frequency and other parameters over which the desirable uniform (as opposed to filamentary) glow discharge occurs, an impedence matching network, one embodiment of which is illustrated schematically by FIG. 2, is added to the power circuit for charging the electrodes **10**. The parameters of this matching network are adjusted for the most stable, uniform operation of the glow discharge. This condition can occur when the reactive power of the plasma reactor is minimized.

FIGS. **3** through **5** represent alternative power supply options having respective attractions. FIGS. **3** corresponds to a configuration wherein the bottom electrode terminal T_1 is connected to ground potential and the top terminal T_2 is charged at the full working potential. FIGS. **4** and **5** are electrical equivalents wherein the T_1 and T_2 voltages are 180° out of phase but at only half the maximum potential. FIG. **4** represents a grounded center tap transformer whereas FIG. **5** represents a solid state power circuit embodiment.

Shown in FIG. **6** are two optional embodiments, the functions of which are to drive a reciprocating gas flow containing active species from the plasma back and forth through the web W. This can be accomplished either by a bellows **35** actuated by a reciprocating shaft **33**, or by a piston **36** activated by a reciprocating shaft **32**. The change in volume of the upper chamber will give rise to a periodic reversal of the pressure differential across the web W, hence, a periodic reversal of the gas flow. As an alternative embodiment, a passageway from behind the piston can be connected to the lower chamber as shown in the dashed line piping **34**.

The FIG. 6 embodiment of the invention provides an electrically grounded screen 30 to support the web W as it is drawn between the opposite material flow slits 23. This configuration attenuates an accumulated electrical charge on the web and also structurally supports the traveling fabric web as a pressure differential membrane between an upper, gas inlet chamber and a lower, vent chamber. This swept flow differential assures an internal saturation of the web W by the gas containing active species from the plasma.

Electric fields employed in a one atmosphere, uniform glow discharge plasma reactor are only a few kilovolts per centimeter, values which, if D. C., would usually be too low to electrically break down the background gas. Gases such as helium and air will break down under such low electric fields, however, if the positive ion population is trapped between the two parallel or uniformly spaced electrodes, this greatly increasing their lifetime in the plasma, while at the same time the electrons are free to travel to the insulated electrode plates where they recombine or build up a surface charge. The most desirable uniform one atmosphere glow discharge plasma is therefore created when the applied frequency of the RF electric field is high enough to trap the ions between the median screen and an electrode plate, but not so high that the electrons are also trapped during a half cycle of the R. F. voltage. The electrons may be trapped by bipolar electrostatic forces.

If the RF frequency is so low that both the ions and the electrons can reach the boundaries and recombine, the particle lifetimes will be short and the plasma will either not initiate or form a few coarse filamentary discharges between the plates. If the applied frequency is in a narrow band in which the ions oscillate between the median screen and an electrode plate, they do not have time to reach either boundary during a half period of oscillation and be carried for long times. If the more mobile electrons are still able to leave the plasma volume and impinge on the boundary surfaces, then the desirable uniform plasma is produced. If the applied RF frequency is still higher so that both electrons and ions are trapped in the discharge, then the discharge forms a filamentary plasma.

Without limiting our invention to any particular theory, we are disposed to a relationship between the electrode spacing, the RMS electrode voltage, and the applied frequency which results in trapping ions but not electrons between the two plates, and produces the desired uniform one atmosphere glow discharge plasma. On FIG. 7 is a schematic of the upper chamber of the one atmosphere glow discharge plasma reactor. The lower boundary of this space is the midplane screen or base, the floating potential of which should remain near ground if the RF power supply output is connected as a push-pull circuit to the two electrodes with a grounded center tap. In the data reported herein, the median screen was grounded through an inductive current choke. In the configuration of FIG. 7, a Cartesian coordinate system is applied as shown, with the applied electric field in the x-direction. The maximum amplitude of the electric field between the grounded median screen and the upper electrode is E_o, and the separation of the screen from the electrodes is the distance d. The median screen, with an exposed sample on it, is assumed not to allow ions through the median plane from the upper chamber to the lower, or vice-versa.

The electric field between the electrodes shown on FIG. 7 is given by

$$E=(E_o \sin \omega t, O, O). \tag{1}$$

It is assumed that the one atmosphere glow discharge operates in a magnetic field free plasma. The equation of motion for the ions or electrons between the two plates is given by a Lorentzian model, in which the electrons and ions collide only with the neutral background gas and, on each collision, give up all the energy they acquired from the RF electric field since the last collision with the neutral gas. The equation of motion for the ions or electrons in the Lorentzian model is given by

$$F=m\dot{v}=-m\nu_c v-eE. \tag{2}$$

where the first term on the right hand side is the Lorentzian collision term, according to which the momentum mv is lost with each collision that occurs with a collision frequency ν_c. The x component of Eq. 2 is given by

$$m\frac{d^2X}{dt^2} + m\nu_c\frac{dx}{dt} = eE_o\sin\omega t. \tag{3}$$

where the electric field E from Eq. 1 has been substituted into the right hand side of Eq. 2. The general solution to Eq. 3 is

$$x=C_1 \sin \omega t=C_2 \cos \omega t, \tag{4}$$

where the constants C_1 and C_2 are given by

$$C_1 = -\frac{eE_o}{m}\,\frac{1}{(\omega^2+\nu_c^2)}, \tag{5}$$

and

$$C_2 = -\frac{\nu_c eE_o}{\omega m}\,\frac{1}{(\omega^2+\nu_c^2)} \tag{6}$$

The one atmosphere helium glow discharge is operated at frequencies between $\omega/2\pi=1$ and 30 KHz, where, for helium at one atmosphere,

$$\nu_{ci} \approx 6.8\times10^9 \textit{ ion collisions/sec.}, \tag{7a}$$

and

$$\nu_{ce} \approx 1.8\times10^{12} \textit{ electron coll./sec.} \tag{7b}$$

The collision frequency for ions and electrons given by Eqs. 7*a* and 7*b* is much greater than the RF frequency, $V_c >> \omega$. The relation $\nu_c >> \omega$ for ions and electrons, implies that C_2 is much greater than the constant C_1, or

$$C_2 \approx \frac{eE_o}{m\omega\nu_c} >> C_1 \tag{8}$$

The time dependent position of an ion or an electron in the electric field between the plates is given by substituting Eq. 8 into Eq. 4, to obtain

$$x(t) \approx -\frac{eE_o}{m\omega\nu_c}\cos\omega t. \tag{9}$$

The RMS displacement of the ion or electron during a half cycle is given by

$$x_{rms} = \frac{\overline{2}}{\pi} \frac{eE_o}{m\omega v_c} \text{ meters.} \tag{10}$$

If V_o is the driving frequency, in Hertz, then the radian RF frequency is given by

$$\omega = 2\pi v_o, \tag{11}$$

and the maximum electric field between the plates can be approximated by the maximum voltage V_o appearing between them,

$$E_o = \frac{V_o}{d} = \frac{\pi V_{rms}}{2d}. \tag{12}$$

If the charge in question moves across the discharge width from the median plane to one of the electrode plates during one full cycle, then we may write

$$x_{rms} \leqq \frac{d}{2}. \tag{13}$$

Equation 13 states that the RMS displacement of the particle has to be less than half the clear spacing in order to have a buildup of positive charge between the plates. In the geometry shown in FIG. 7, the distance d is identified with the distance between the grounded median screen and the energized electrode. Substituting Eqs. 11 to 13 into Eq. 10 yields the relationship

$$\frac{d}{2} \approx \frac{eV_{rms}}{2\pi m v_o v_c d}. \tag{14}$$

If we now solve for the critical frequency v_o above which charge buildup should occur in the plasma volume, we have

$$v_o \approx \frac{eV_{rms}}{\pi m v_c d^2} \text{ Hz.} \tag{15}$$

In Eq. 15, the collision frequency va is given by Eqs. *7a* or *7b* for ions or electrons, respectively, at one atmosphere, and the RMS voltage is that which bounds the upper and lower limit of the uniform discharge regime.

The range of parameters over which we have operated a one atmosphere, uniform glow discharge plasma reactor is given in Table I. The nominal pressure at which this discharge has been operated is one atmosphere. The variation of several torr shown in Table I is not intended to represent the day-to-day fluctuations of barometric pressure, but the pressure differential across the midplane screen which is intended to drive active species from the upper plasma through the fabric being exposed. The RMS power shown in Table I is the net power delivered to the plasma, less the reactive power which does not appear in the plasma. The total volume of plasma between the two electrode plates is given by

$$S = 0.93\ d(cm) \text{ liters.} \tag{16}$$

where d is the separation of a plate from the median screen in centimeters.

The power densities shown in Table I are far below those of electrical arcs or plasma torches, but also are several orders of magnitude higher than the power densities associated with some other forms of plasma treatment such as corona discharges. The power densities of the one atmosphere glow discharge plasma are generally low enough not to damage exposed fabrics, but are also enough higher than coronal plasmas used for surface treatment that they should provide far more active species than the latter. The plasma parameters, such as electron kinetic temperature and number density are somewhat speculative at this early stage in the development of our invention. A few results from probing the plasma midplane with a floating Langmuir probe indicates that the plasma, without grounding the midplane screen, will float to positive potentials of several hundred volts. The ion kinetic temperatures are very likely close to that of the room temperature atoms with which they frequently collide at these high pressures; the electrons apparently remain numerous and energetic enough to excite the neutral background atoms, hence making this a glow discharge. The existence of excited states which emit visible photons implies that the electron population has a kinetic temperature of at least an electron volt. The diagnostic difficulties of measuring plasma parameters at this high pressure are very severe, since ordinary Langmuir probing technique cannot be applied due to the short mean free paths of the electrons compared to a Debye distance. Electron number densities, however, may be measured by microwave interferometric techniques.

TABLE I

OPERATING CHARACTERISTICS OF THE ONE ATMOSPHERE GLOW DISCHARGE PLASMA REACTOR

working gas = He, He + 1-7% O_2, Ar, Ar + He, Ar + 1-7% O_2, and atmospheric air
frequency = 1 KHz to 100 KHz
voltage = 1.5-9.5 kV_{rms} plate to plate
electrode gap d = 0.8-3.2 cm
pressure = 760 +15, −5 torr
RMS power = 10 watts to 150 watts
power density = 4-120 mW/cm^3
plasma volume = 0.7-3.1 liters

On FIGS. 8 and 9 are shown two waveforms of voltage and current taken in helium at the same electrode separation and gas flow conditions, but at two different frequencies. FIG. 8 was taken in the uniform glow discharge regime at a frequency of 2.0 kHz, and FIG. 9 was taken in the filamentary discharge regime at a frequency above the uniform plasma operating band at 8.0 kHz. The high output impedance of our RF power supply results in a voltage waveform (trace B) that is very close to sinusoidal. The reactive current waveform (trace C) is interrupted by a breakdown of the plasma twice each cycle, once when the voltage is positive, and once when the voltage is negative. Trace A shows the reactive current waveform at the same voltage and operating conditions, but in air, rather than helium. There was no perceptible plasma present in air under these conditions, and the power is completely reactive. This purely reactive current of trace A was subtracted from the total plasma current in trace C, to yield trace D. The instantaneous power deposited in the plasma (trace E) is found by multiplying the excess plasma current above the reactive current (trace D) by the voltage at that point (trace B). The average power is found by integrating over the duration of the pulses shown, and dividing by this duration. It is in this manner that the power and power density into the plasma were

calculated for these highly nonsinusoidal current waveforms. FIGS. 8 for the uniform discharge and 9 for the filamentary discharge show characteristically different power waveforms in trace E; this is a method of distinguishing the uniform from the filamentary discharge.

The plasma power is of interest because it is proportional to the production rate of active species in the plasma; the reactive power is significant because it determines the required power handling rating of the plasma power supply and associated equipment. The total power is the sum of plasma and reactive power. On FIG. 10 is shown a log-log plot of the plasma and total power density in milliwatts per cubic centimeter, as functions of the RMS voltage applied to the parallel plates. The active plasma volume in FIG. 10 was 1.63 liters, with a separation between -the median screen and each plate of d=1.75 centimeters in a plasma of helium gas. On FIG. 11 is a similar presentation of the power density plotted on log-log coordinates as a function of the frequency. The approximate bound of the uniform plasma discharge regime is shown by the arrow. These data were taken in helium gas for the same plasma volume and electrode separation as FIG. 10.

EXAMPLE 1

In a first operational example of the invention, the FIG. 1 described physical apparatus sustained a glow discharge plasma in one atmosphere of helium at standard temperature with a separation distance s of 3.0 cm between plates 10. The plates were energized with a 4.4 KV rms working potential. Holding these parameters constant, R. F. frequency was increased as an independent variable. As the dependent variable, FIG. 12 charts the corresponding breakdown current phase angle as determined relative to the voltage waveform node. Similarly, FIG. 13 charts the total power, including reactive and plasma input power required to sustain the plasma at the respective R. F. frequencies.

EXAMPLE 2

In a second operational example of the invention, the FIG. 1 described physical apparatus is used to sustain a glow discharge plasma in one atmosphere of helium at standard temperature with a separation distance s of 1.0 cm between plates 10. In this example, the R. F. frequency was held constant at 30 KHz while plate potential was manipulated as the independent variable and current breakdown phase angle, Θ, (Table 2) and total power, P, (Table 3) measured as dependent variables.

TABLE 2

V(KV)	1	1.5	2	2.5	3	3.5
θ(deg)	28	40	61	46	65	76.5

TABLE 3

V(KV)	1	1.5	2	2.5	3	3.5
P(W)	7	13	22	57	50	44.9

EXAMPLE 3

A third operational example of the invention included a one atmosphere environment of helium between a 1 cm separation distance s between plate electrodes 10 charged at 1.5 KV rms potential. The R. F. frequency was manipulated as the independent variable. As a measured dependent variable, Table 4 reports the corresponding phase angle Θ of breakdown current. The measured dependent variable of Table 5 reports the corresponding total power consumption data.

TABLE 4

f(KHz)	10	20	30	40	50	60	70	80	90	100
θ(deg)	43	32	43	52	54	61	60	56	45	22.5

TABLE 5

f(KHz)	10	20	30	40	50	60	70	80	90	100
P(W)	5	8	11	19	35	43	47	57	89	124

EXAMPLE 4

The largest volume helium plasma of 3.1 liters was achieved with the above described apparatus at a 3.7 cm plate separation having a 5 KV rms potential at an R. F. frequency of 4 KHz.

Meltblown webs formed from nylon, poly(ethylene terephthalate), polypropylene and polyethylene have been processed by exposure to the glow discharge plasma described herein to produce desired material characteristics, increased wettability and re-wettability.

Wettability of a material is objectively measured by either or both of two tests including (a) the angle of a water bead supported on the material surface and (b) the time required to wick along a predetermined material length.

By such tests, it was determined that polypropylene, nylon, polyester and polyethylene film experienced a significant wettability and re-wettability improvement after a 2.5 minute plasma exposure as evidenced by a greatly reduced bead angle.

A poly(ethylene terephthalate) web, after 2.5 minutes of glow discharge plasma exposure to a 5 KV, 4 KHz across a 4.5 cm plate separation, experienced a 0° surface bead angle and a 37.37 second wicking rate determined by the INDA standard absorption test. Prior to plasma exposure, the web had a large surface bead angle and no wicking capacity.

Similarly, after only 60 seconds of exposure to the same plasma, a nylon web, having a high surface bead angle and no wicking capacity enjoyed a 0° surface bead angle and a 16.61 second wicking rate (INDA standard test) upon wetting and re-wetting.

In another test set, two different meltblown webs Poly(ethylene terephthalate) and polypropylene (PET and PP), were treated by the one atmosphere glow discharge plasma with helium or helium plus active gases as the working gas for a treating time period from half minute to two minutes. The power supply voltage was from 1,000 V_{rms} to 4,000 V_{rms} and the frequency was from 1 kHz to 100 kHz. The webs had a fiber size of 2 to 2.5 microns, a pore size of 20–25 microns, and a porosity of 90%. Table 6 lists some initial results from these treatments.

Wettability was justified by contact angle, wickability, and wetout of the liquid through web thickness and on the web surface. Wickability was measured according to INDA standard (1st 10.1-92), in which time was measured for the liquid (double D's water) to rise 2.4 cm high. Physical fiber surface change was analyzed by photomicrographs taken using the ETEC Auto Scan electron microscope for a magnification of 2,000× to 4,000×.

TABLE 6

	Treating Conditions			Wettability			
Sample	Time(s)	gases	kV_{rms}	Contact Angle	Wicking Rate(s)	Thickness Wettability	Surface Wettability
PP 0.35 oz	60	He, O_2	3.5	reduced	not sig.	90%	good
PP 0.35 oz	60	He, O_2	3.0	unchanged	no	75%	increased
PET 1 oz	90	He	2.3	0	31.74	good	good

Although expansive data is not presently available, it is to be noted that a uniform glow discharge plasma has been sustained by the FIG. 1 apparatus with a one atmosphere ambient air environment and an 8 kV/cm electric field.

Having fully disclosed our invention and the presently preferred embodiments and best modes of practice,

We claim:

1. A method for improving the surface characteristics of a web comprising the steps of generating in a gas maintained at about atmospheric pressure a sustained, uniform glow discharge plasma having active species between a pair of spaced electrodes, wherein said generating step includes energizing said electrodes at a voltage of at least about 1 kV rms at frequencies of about 1 to 100 kHz, and positioning said web between said electrodes and within said plasma for a period of time and pressure differentially driving the active species through said web.

2. A method as described by claim 1 wherein a volume defined by the space between said electrodes is charged with said gas.

3. A method as described by claim 2 wherein said gas is helium.

4. A method as described by claim 2 wherein said gas is a mixture of helium and air.

5. A method as described by claim 2 wherein said gas is argon.

6. A method as described by claim 2 wherein said gas is a mixture of argon and air.

7. A method as described by claim 2 wherein said gas is a mixture of argon and helium.

8. A method as described by claim 2 wherein said gas is atmospheric air.

9. A method as described by claim 2 wherein said gas is nitrous oxide.

10. The method of claim 1 wherein said voltage is in the range of about 1 kV to 5 kV rms.

11. The method of claim 1 wherein said voltage is in the range of about 1.5 kv to 9.5 kV

12. The method of claim 2 wherein said gas is a noble gas.

* * * * *

US005414324A

United States Patent [19]

Roth et al.

[11] Patent Number: 5,414,324

[45] Date of Patent: * May 9, 1995

[54] ONE ATMOSPHERE, UNIFORM GLOW DISCHARGE PLASMA

[75] Inventors: John R. Roth; Peter P. Tsai; Chaoyu Liu; Mounir Laroussi; Paul D. Spence, all of Knoxville, Tenn.

[73] Assignee: The University of Tennessee Research Corporation, Knoxville, Tenn.

[*] Notice: The portion of the term of this patent subsequent to Feb. 7, 2012 has been disclaimed.

[21] Appl. No.: 145,786

[22] Filed: Oct. 29, 1993

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 68,508, May 28, 1993.

[51] Int. Cl.[6] H01J 7/24

[52] U.S. Cl. .... 315/111.21; 315/111.51; 118/723 E

[58] Field of Search .... 315/111.21, 111.51; 118/723 E, 723 I; 313/231.31

[56] References Cited

U.S. PATENT DOCUMENTS

5,147,493	9/1992	Nishimura	315/111.51
5,272,417	12/1993	Ohmi	315/111.21
5,309,063	5/1994	Singh	315/111.51

FOREIGN PATENT DOCUMENTS

0068775	1/1983	European Pat. Off. .	
0117561	9/1984	European Pat. Off. .	
0292582	8/1991	Germany	315/111.21
0200529	11/1983	Japan	313/111.21
1177374	8/1986	Japan	118/723 E
0002544	1/1987	Japan	118/723 E
62-235339	10/1987	Japan .	
4225226	8/1992	Japan	315/111.21

OTHER PUBLICATIONS

Authors: Von Engel, A.; Seeliger, R.; & Steenbeck, M. Title: On The Glow Discharge At High Pressure Publication: *Zeit, fur Physik*, vol. 85 (1933) pp. 144–160.

Authors: Wakida, T.; Kawamura, H.; Han, L.; Hwan Kim, K.; Goto, T.; & Takagishi, T. Title: Changes In Surface Properties Of Poly(Ethylene Terphthalate) Treated With Low Temperature Plasma: Effect Of Pretreatment With Dimethylformamide Publication: *sen-i qakkaishi*, vol. 43, No. 7 (1987).

Authors: Wakida, T.; Kawamura H.; Song, J. C.; Goto T.; Takagishi, T. Title: Surface Free Energy Poly-(Ethylene Terephthalate) And Nylon 6 Films Treated With Low Temperature Plasma Publication: *Seni-I Gakkaishi*, vol. 43, No. 7 (1987).

Authors: Kogoma, M.; Kasai, H.; Takahashi, K.; Moriwaki, T. & Okazaki, S. Title: Wettability Control Of A Plastic Surface By CF_4 Plasma And Its Etching Effect Publication: *J. Phys. D: Appl. Phys.*, vol. 20 (1987).

Authors: Kanazawa, S.; Kogoma, M.; Moriwaki, T.; & Okazaki, S. Title: Stable Glow Plasma At Atmospheric Pressure Publication: *J. Physics D: Appl. Phys.*, vol. 21 (1988) pp. 838–840.

Author: Rakowski, W. Title: Plasma Modification Of Wool Under Industrial Conditions Publication: *Melliand Textilberichte*, vol. 70 (1989) pp. 780–785.

Authors: Yokoyama, T.; Kogoma, M.; Moriwaki, T.; & Okazaki, S. Title: The Mechanism Of The Stabilisation Of Glow Plasma At Atmospheric Pressure Publication: *J. Physics D. App. Phys.*, vol. 23 (1990) pp. 1125–1128.

Authors: Naoki Kanda; Masuhiro Kogoma; Hiroshi

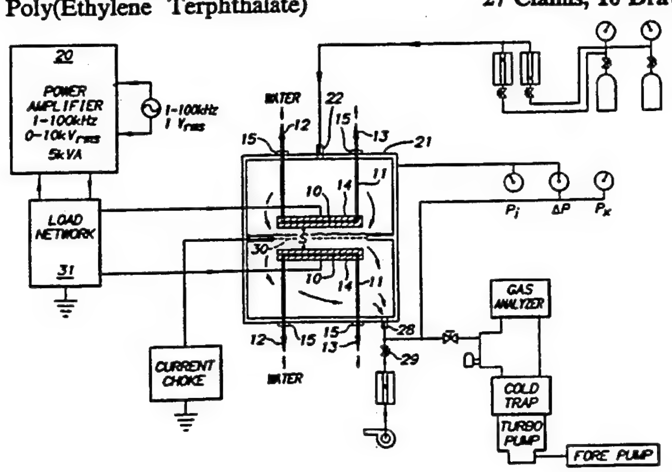
(List continued on next page.)

Primary Examiner—Robert J. Pascal
Assistant Examiner—Darius Gambino
Attorney, Agent, or Firm—Weiser & Associates

[57] ABSTRACT

A steady-state, glow discharge plasma is generated at one atmosphere of pressure within the volume between a pair of insulated metal plate electrodes spaced up to 5 cm apart and R.F. energized with an rms potential of 1 to 5 KV at 1 to 100 KHz. Space between the electrodes is occupied by air, nitrous oxide, a noble gas such as helium, neon, argon, etc. or mixtures thereof. The electrodes are charged by an impedance matching network adjusted to produce the most stable, uniform glow discharge.

27 Claims, 10 Drawing Sheets



OTHER PUBLICATIONS

Jimmo; Hiroshi Uchiyama & Sachiko Okazaki Title: Atmospheric Pressure Glow Plasma And Its Application To Surface Treatment And Film Deposition. Publication: *International Symposium on Plasma Chemistry*, Symposium Proceedings, vol. 3, Bochum, Germany, Aug. 4–9, 1991.

Authors: Liu, C.; Chen, D.; & Roth, J. R. Title: Characteristics Of A Steady-State, Low Power Glow Discharge At Atmospheric Pressure Publication: *APS Bulletin*, vol. 37, No. 6 (1992) p. 1563.

Authors: Roth, J. R.; Liu, C.; & Laroussi, M. Title: Experimental Generation Of A Steady-State Glow Discharge At Atmospheric Pressure Publication: Paper 5P-21, *Proc. 1992 IEEE International Conference on Plasma Science*, Tampa, Fla., IEEE Catalog No. 92-TH0460-6, ISBN 0-7803 0716-X (1992), pp. 170–171.

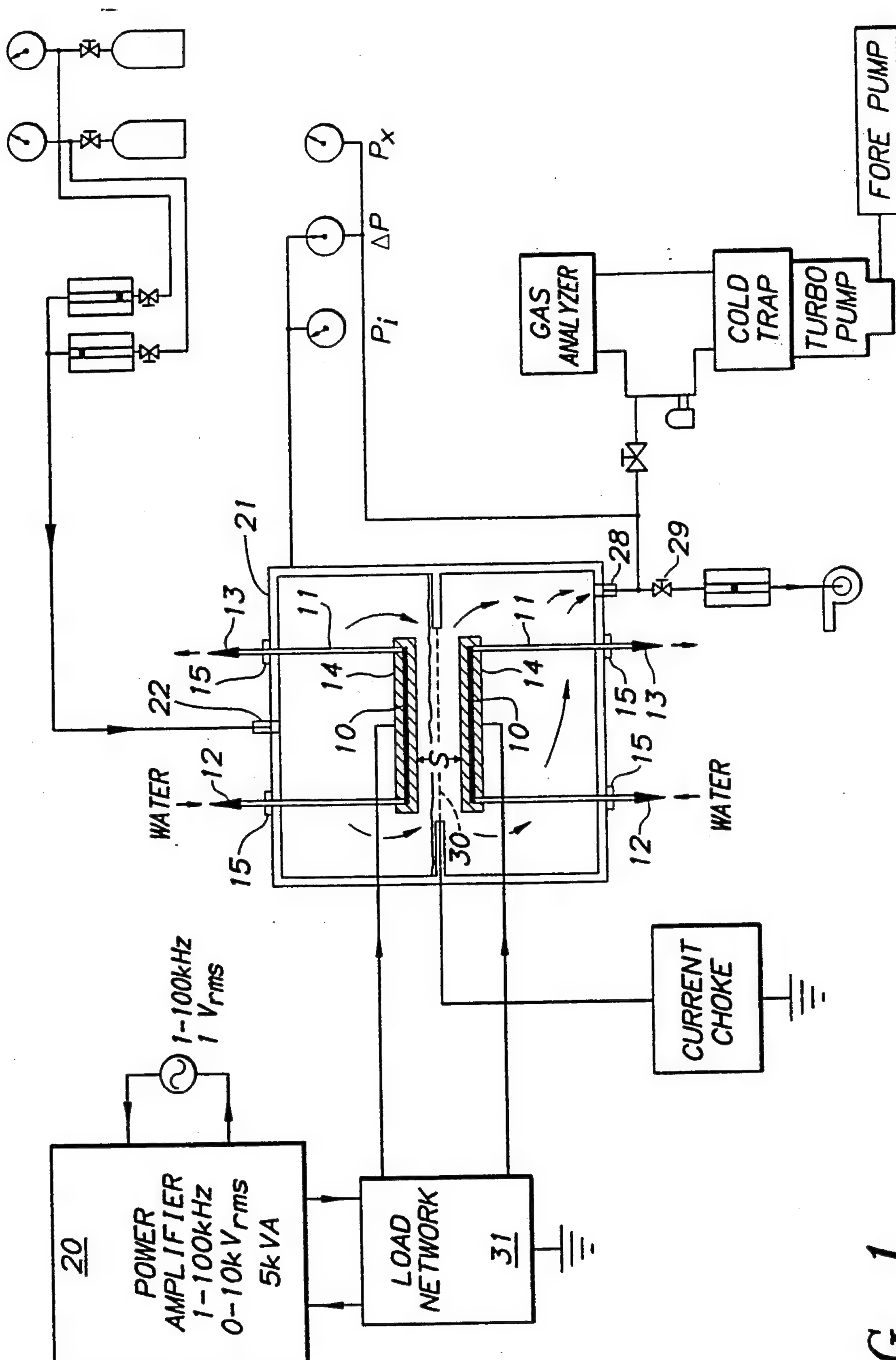
Authors: Reitz, H.; Schwarz, R.; Salge, J. G. H. Title: Power Modulation For Dielectric Barrier-Discharges Publication: Paper presented at *Twentieth Power Modulator Symposium*, 1992.

Author: Rakowski, W. Title: Effect And Cost Of Plasma Treatment Of Polypropylene Melt Blown Webs Publication: *Second Annual TANDEC Conference*, 13–16 Oct., 1992.

Authors: Liu, C. Title: Plasma-Related Characteristics Of A Steady-State Glow Discharge At Atmospheric Pressure Publication: Presented at the *1993 Sigma XI Graduate Student Paper Competition, The University of Tennessee, Knoxville, Tenn.* on Mar. 4, 1993.

Authors: Roth, J. R.; Spence, P. D.; Liu, C. Title: Plasma-Related Characteristics of A Steady-State Glow Discharge At Atmospheric Pressure Publication: Paper 2P-18, *Proc. 1993 IEEE International Conference on Plasma Science*, Vancouver, B. C. IEEE Catalog No. 93-CH3334-0, ISBN 0-7803-1360-7 (1993), p. 129.

Authors: Roth, J. R.; Spence, P. D.; Liu, C. Title: Preliminary Measurements Of The Plasma Properties Of A One Atmosphere Glow Discharge Plasma Publication: Paper Present at *35th Annual Meeting of the APS Division of Plasma Physics*, St. Louis, Mo., Nov. 1–5, 1993; *APS Bulletin*, Series II, vol. 38, No. 10 (1993), p. 1901.



FORE PUMP
TURBO PUMP
COLD TRAP
GAS ANALYZER
P_x
ΔP
P_i
21
22
13
15
11
14
10
12
WATER
28
29
S
30
CURRENT CHOKE
1-100kHz 1 V_{rms}
20
POWER AMPLIFIER 1-100kHz 0-10k V_{rms} 5kVA
LOAD NETWORK
31

FIG. 1

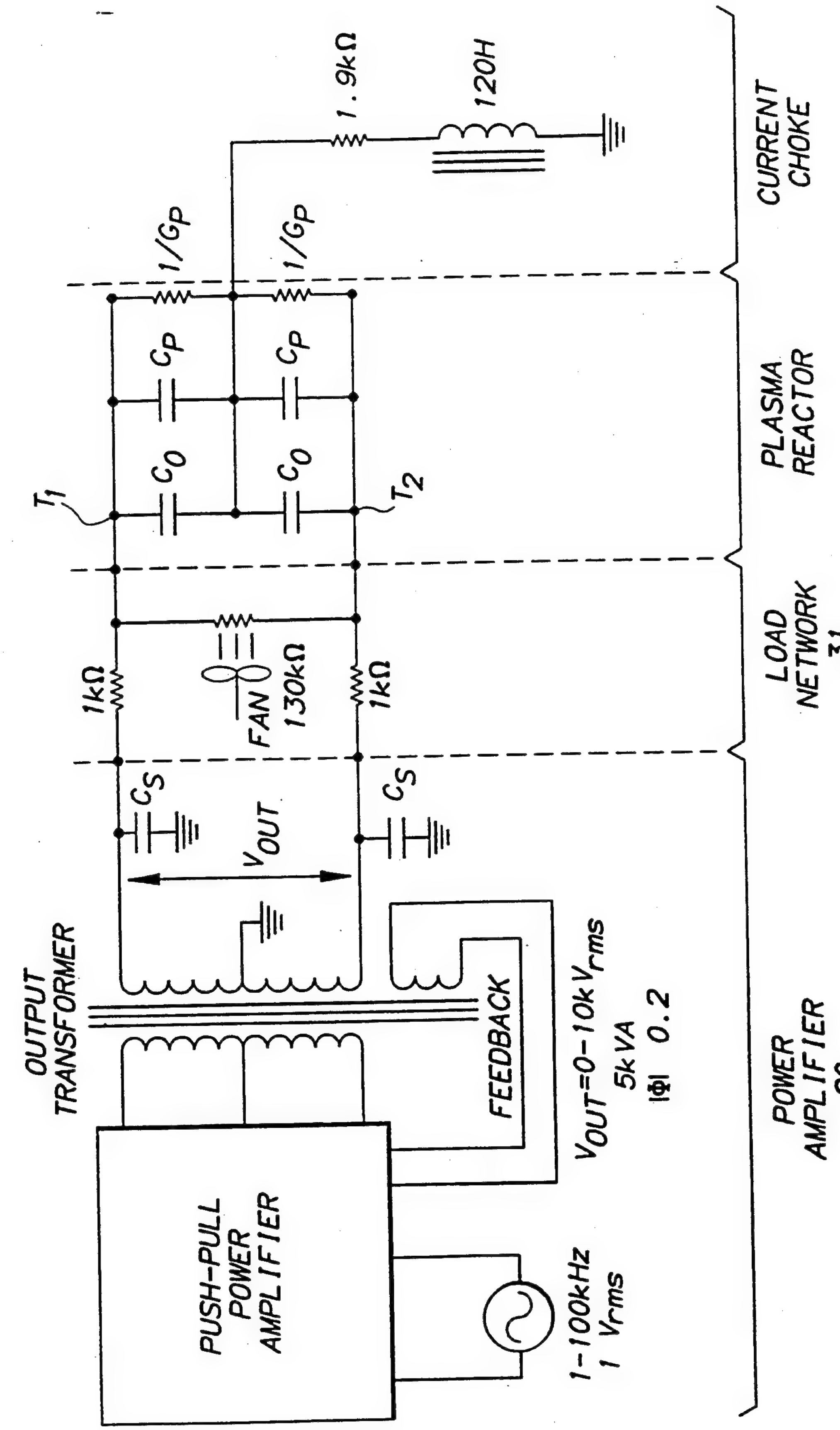

1.9kΩ
120H
CURRENT CHOKE
1/G_P
1/G_P
C_P
C_P
C_O
C_O
T_1
T_2
PLASMA REACTOR
1kΩ
FAN 130kΩ
1kΩ
LOAD NETWORK 31
C_S
C_S
V_{OUT}
OUTPUT TRANSFORMER
FEEDBACK
V_{OUT}=0–10k V_{rms}
5k VA
1Φ 0.2
POWER AMPLIFIER 20
PUSH-PULL POWER AMPLIFIER
1–100kHz
1 V_{rms}

FIG. 2

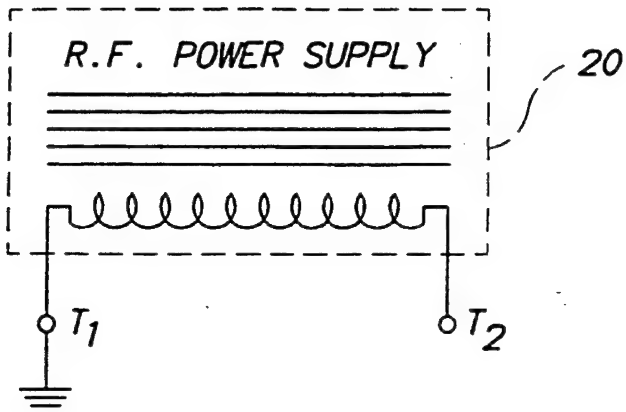


FIG. 3

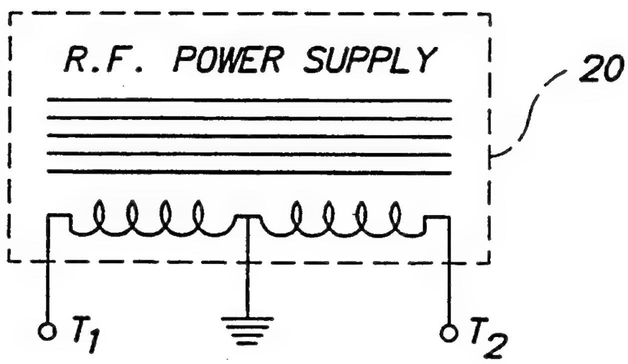


FIG. 4

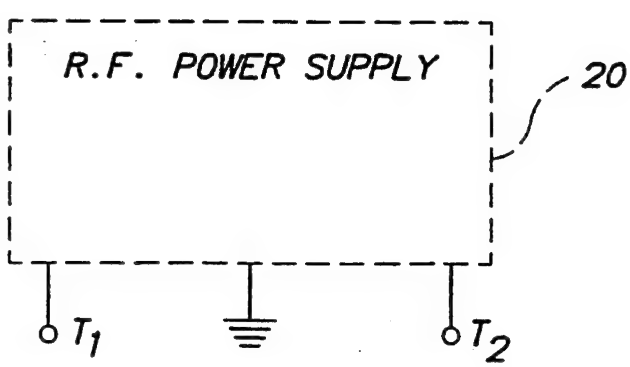


FIG. 5

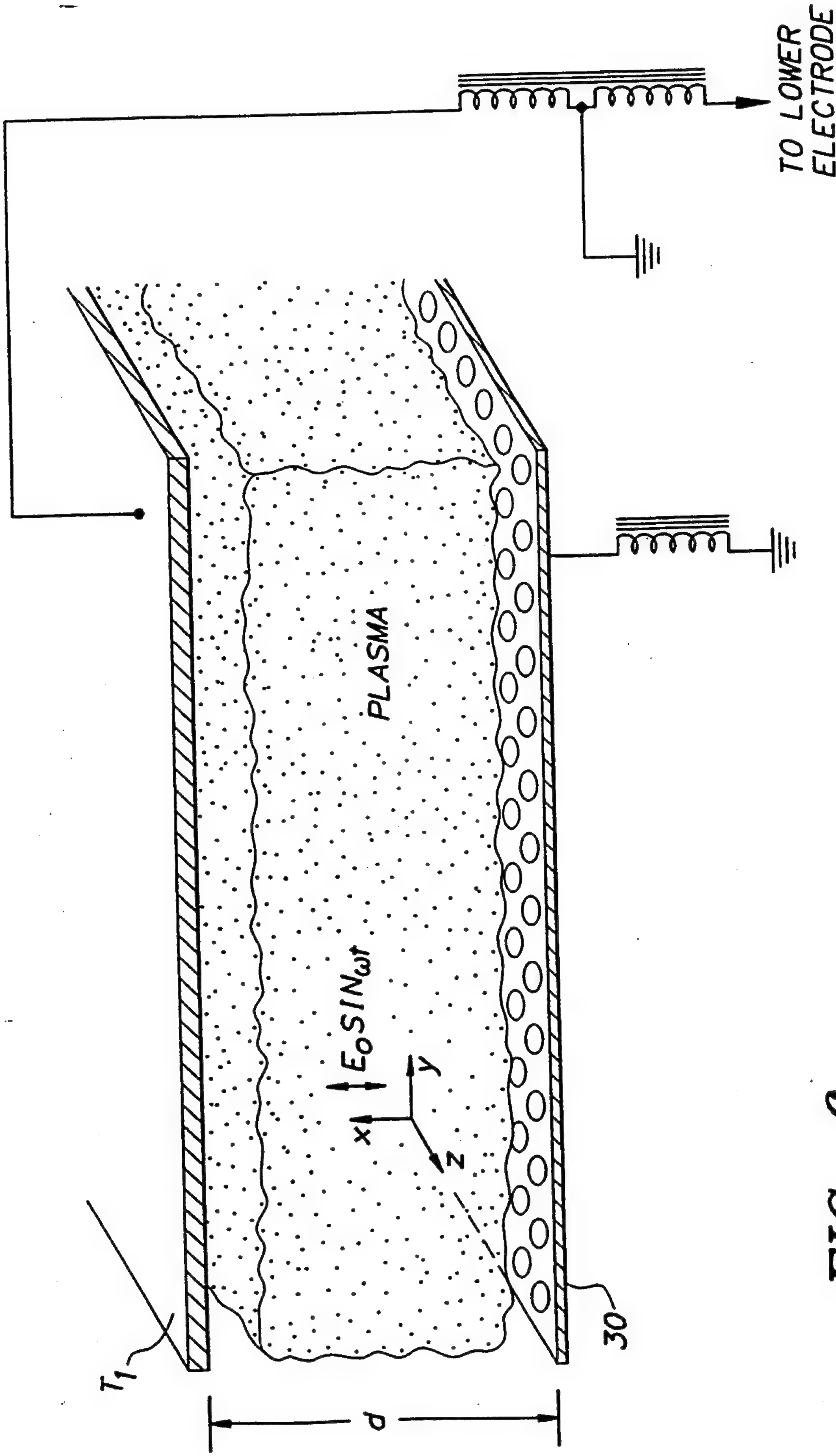


FIG. 6

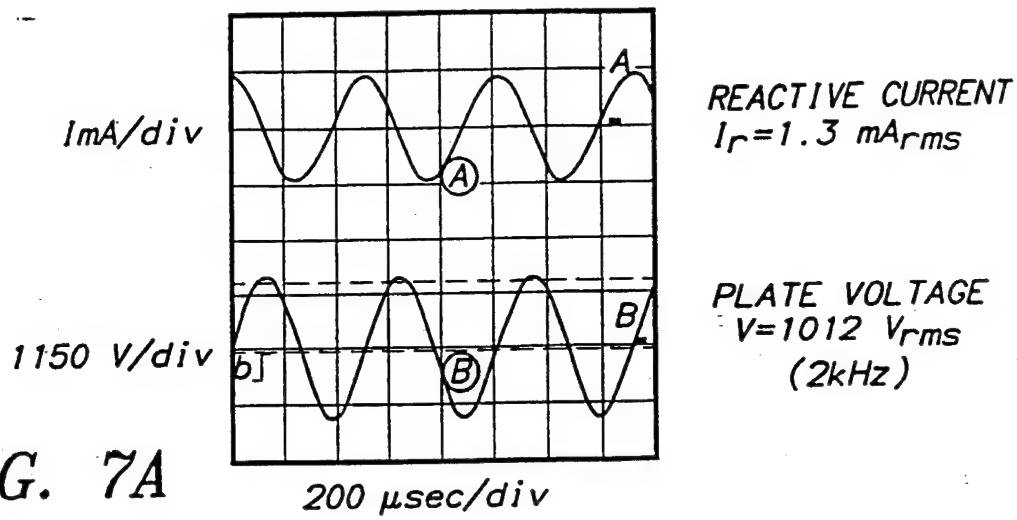


FIG. 7A

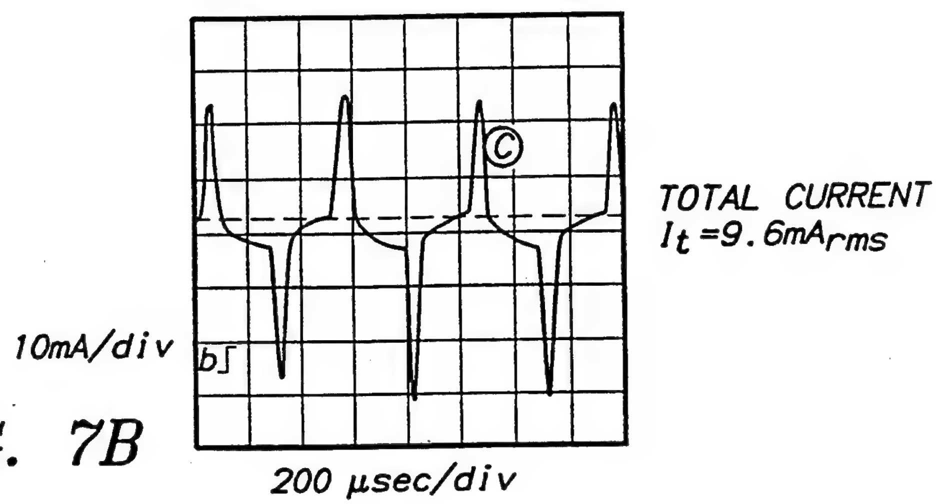


FIG. 7B

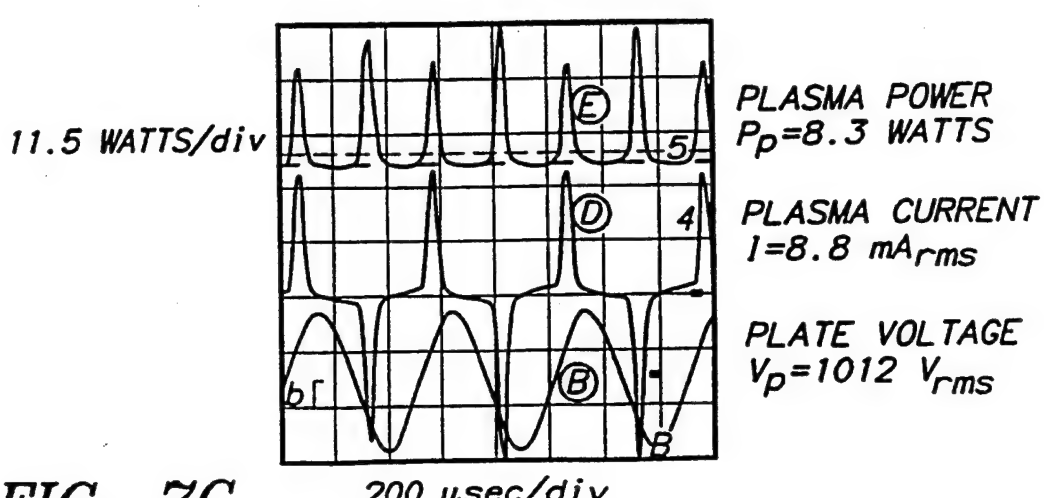


FIG. 7C

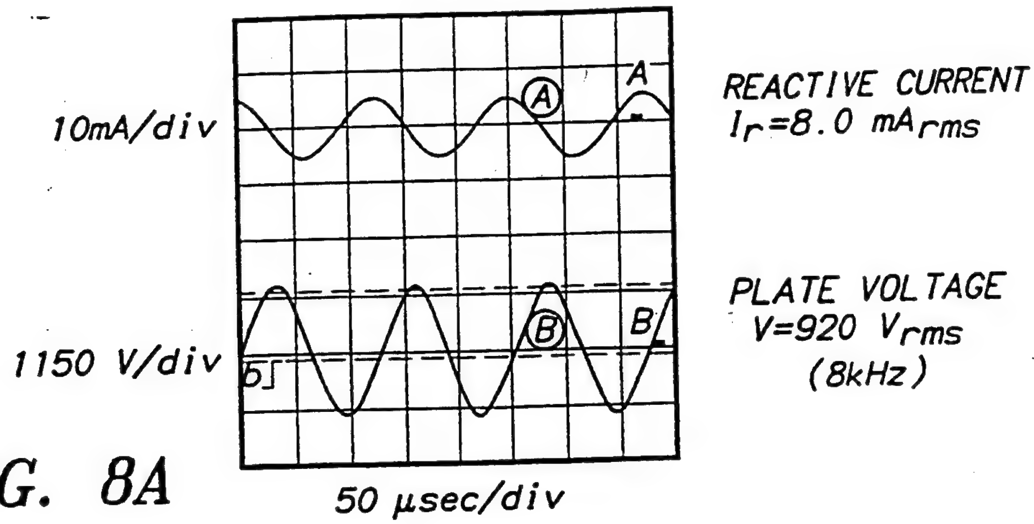


FIG. 8A

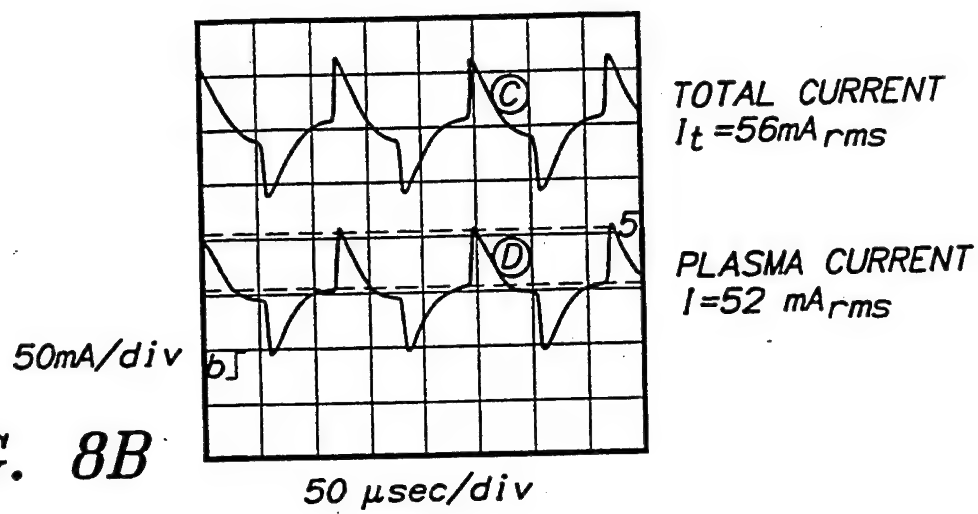


FIG. 8B

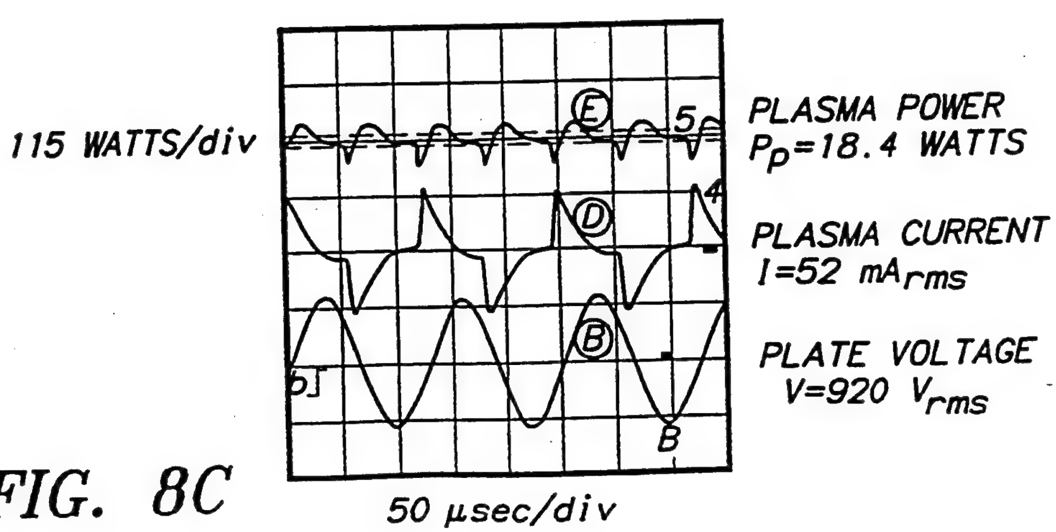
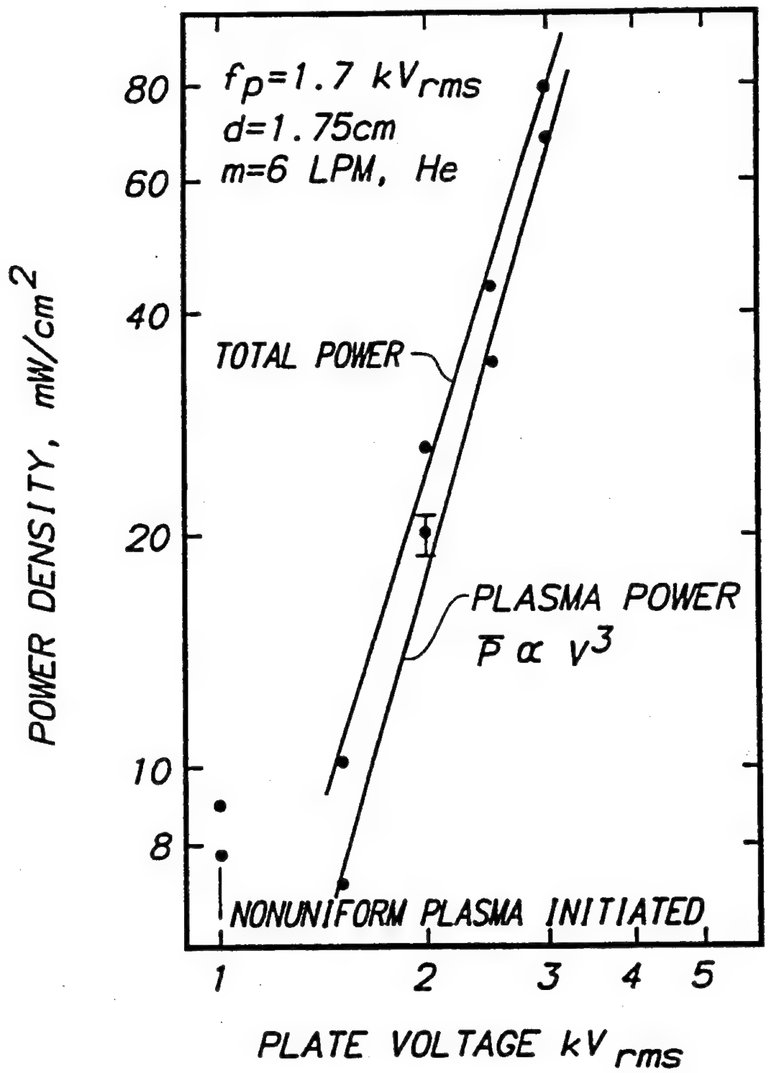
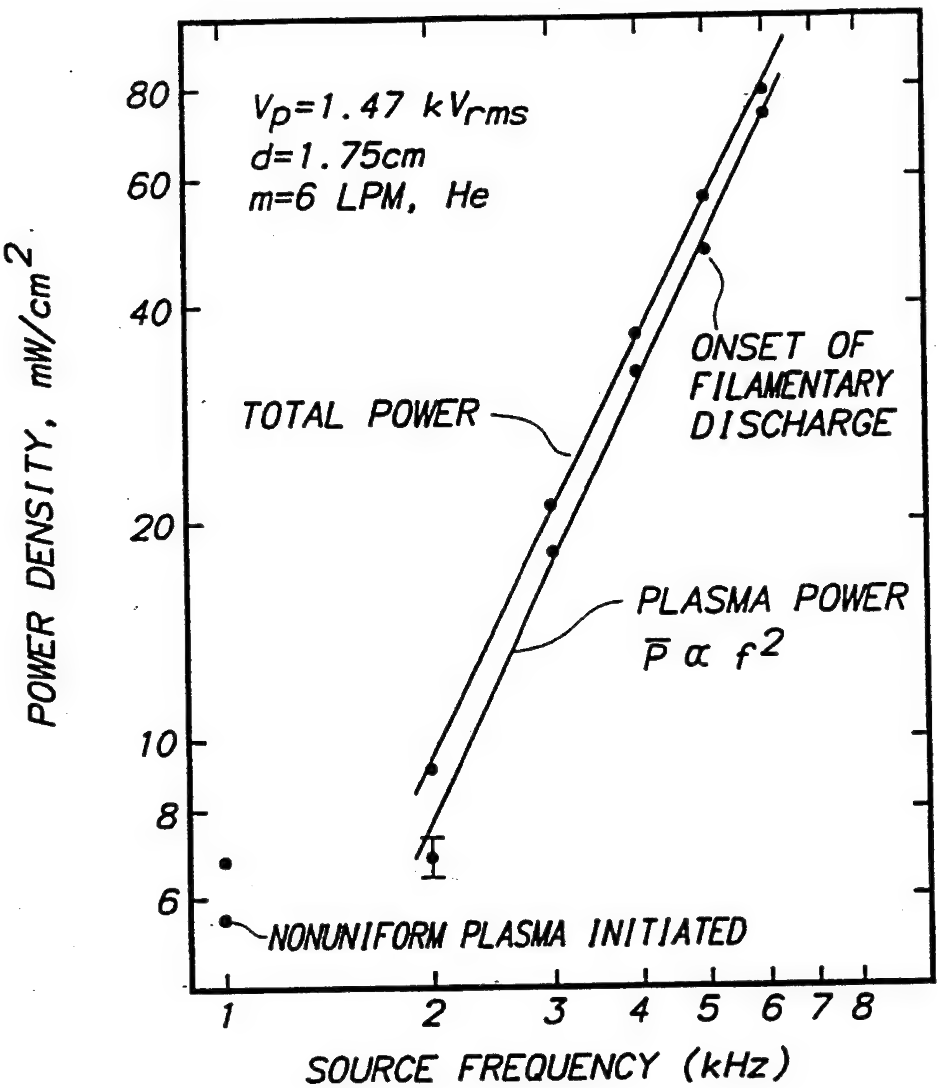


FIG. 8C



f_p=1.7 kV$_{rms}$
d=1.75cm
m=6 LPM, He
TOTAL POWER
PLASMA POWER
$\overline{P} \propto V^3$
NONUNIFORM PLASMA INITIATED
POWER DENSITY, mW/cm^2
PLATE VOLTAGE kV$_{rms}$
80
60
40
20
10
8
1
2
3
4
5

FIG. 9



V_p=1.47 kV_{rms}
d=1.75cm
m=6 LPM, He
80
60
40
20
10
8
6
POWER DENSITY, mW/cm^2
TOTAL POWER
ONSET OF FILAMENTARY DISCHARGE
PLASMA POWER
$\overline{P} \propto f^2$
NONUNIFORM PLASMA INITIATED
1
2
3
4
5
6
7
8
SOURCE FREQUENCY (kHz)

FIG. 10

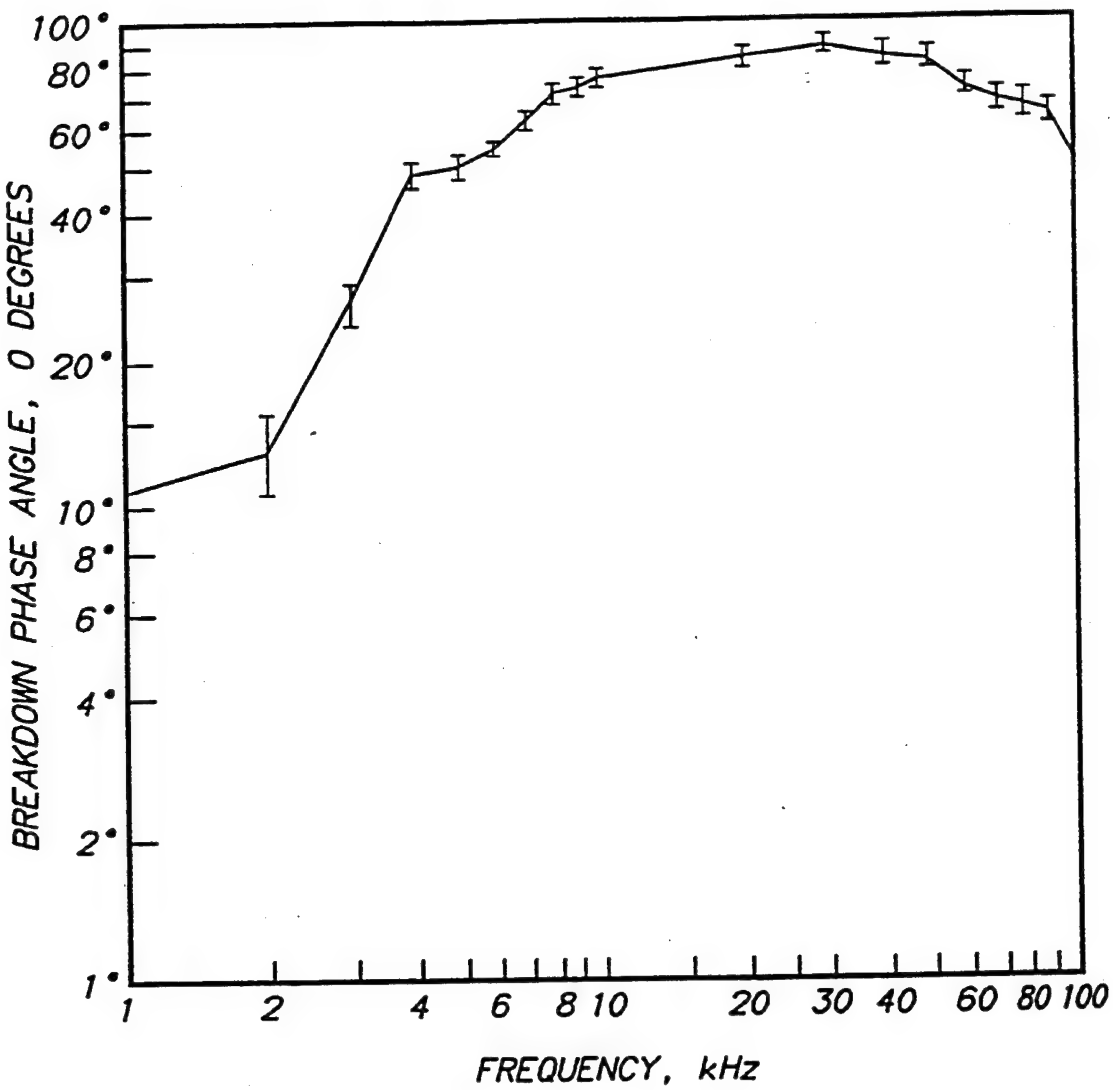
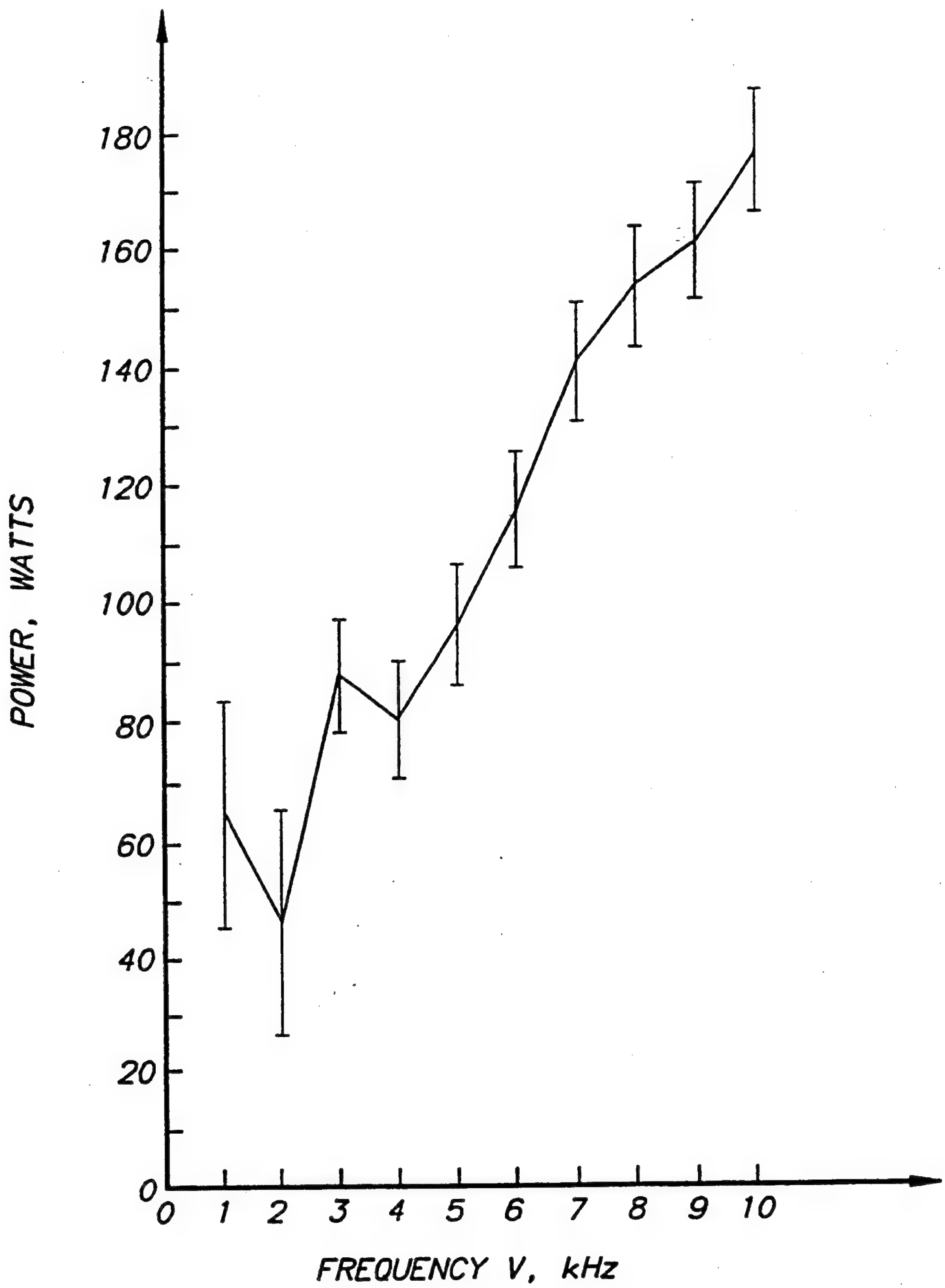

100°
80°
60°
40°
20°
10°
8°
6°
4°
2°
1°
BREAKDOWN PHASE ANGLE, θ DEGREES
1
2
4
6
8
10
20
30
40
60
80
100
FREQUENCY, kHz

FIG. 11



180
160
140
120
100
80
60
40
20
0
POWER, WATTS
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY V, kHz

FIG. 12

ONE ATMOSPHERE, UNIFORM GLOW DISCHARGE PLASMA

LICENSE RIGHTS

The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of contract No. AFOSR 89-0319 awarded by The U.S. Air Force.

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a Continuation-In-Part of U.S. patent application Ser. No. 08/068,508 filed May 28, 1993.

BACKGROUND OF THE INVENTION

1. Field of Invention

The present invention relates to methods and apparatus for generating low power density glow discharge plasmas at atmospheric pressure.

2. Description of the Prior Art

In the discipline of physics, the term "plasma" describes a partially ionized gas composed of ions, electrons and neutral species. This state of matter may be produced by the action of either very high temperatures, strong constant electric fields or radio frequency (R.F.) electromagnetic fields. High temperature or "hot" plasmas are represented by celestial light bodies, nuclear explosions and electric arcs. Glow discharge plasmas are produced by free electrons which are energized by imposed direct current (DC) or R.F. electric fields, and then collide with neutral molecules. These neutral molecule collisions transfer energy to the molecules and form a variety of active species which may include photons, metastables, atomic species, free radicals, molecular fragments, monomers, electrons and ions. These active species are chemically active and/or physically modify the surface of materials and may therefore serve as the basis of new surface properties of chemical compounds and property modifications of existing compounds.

Very low power plasmas known as dark discharge coronas have been widely used in the surface treatment of thermally sensitive materials such as paper, wool and synthetic polymers such as polyethylene, polypropylene, polyolefin, nylon and poly(ethylene terephthalate). Because of their relatively low energy content, corona discharge plasmas can alter the properties of a material surface without damaging the surface.

Glow discharge plasmas represent another type of relatively low power density plasma useful for non-destructive material surface modification. These glow discharge plasmas can produce useful amounts of visible and ultraviolet radiation. Glow discharge plasmas have the additional advantage therefore of producing visible and UV radiation in the simultaneous presence of active species. However, glow discharge plasmas have heretofore been successfully generated typically in low pressure or partial vacuum environments below 10 torr, necessitating batch processing and the use of expensive vacuum systems.

Conversely, the generation of low power density plasmas at one atmosphere is not entirely new. Filamentary discharges between parallel plates in air at one atmosphere have been used in Europe to generate ozone in large quantities for the treatment of public water

supplies since the late 19th century. Filamentary discharge plasmas are dramatically distinguished from uniform glow discharge plasmas. Such filamentary discharges, while useful for ozone production, are of limited utility for the surface treatment of materials, since the plasma filaments tend to puncture or treat the surface unevenly.

It is, therefore, an object of the present invention to teach the construction and operating parameters of a continuous glow discharge plasma sustained at a gas pressure of about one atmosphere or slightly greater.

INVENTION SUMMARY

This and other objects of the invention to be subsequently explained or made apparent are accomplished with an apparatus based upon a pair of electrically insulated metallic plate electrodes. These plates are mounted in face-to-face parallel or uniformly spaced alignment with means for reciprocatory position adjustment up to at least 5 cm of separation. Preferably, the plates are water cooled and covered with a dielectric insulation.

To broaden the range of operating frequency and other parameters over which the desirable uniform (as opposed to filamentary) glow discharge is observed, an impedance matching network is added to the circuit for charging the electrodes. The parameters of such a matching network are adjusted for the most stable, uniform operation of the glow discharge. This condition can occur when the reactive power of the plasma reactor is minimized.

A radio frequency power amplifier connected to both plates delivers up to several hundred watts of power at a working voltage of 1 to at least 5 KV rms and at 1 to 100 KHz. To assist the starting of the plasma, the electrical discharge from a standard commercial Tesla coil may be briefly applied to the volume between the R.F. energized plates. An electric field established between the metallic plate electrodes must be strong enough to electrically break down the gas used, and is much lower for helium and argon than for atmospheric air. The RF frequency must be in the right range, discussed below, since if it is too low, the discharge will not initiate, and if it is too high, the plasma forms filamentary discharges between the plates. Only in a relatively limited frequency band will the atmospheric glow discharge plasma reactor form a uniform plasma without filamentary discharges.

To stabilize the plasma and discourage the formation of plasma filaments, an inductor may be connected from the median plane to ground.

At least in the volume between the plates wherein the glow discharge plasma is established, a one atmosphere charge of helium, argon or other gas or mixture of gases is established and maintained.

The median plane between two parallel electrodes may or may not contain an insulating or electrically conductive screen or plate which may be used to support exposed materials in the glow discharge plasma environment. If electrically conductive, the median screen or plate may be electrically floating or grounded.

BRIEF DESCRIPTION OF THE DRAWINGS

Relative to the drawings wherein like reference characters designate like or similar elements throughout the several figures of the drawings:

FIG. 1 is a schematic of the present invention component assembly.

FIG. 2 represents a preferred embodiment of the electrical circuit, including an impedance matching network and a grounded midplane screen connected to ground through an inductor.

FIGS. 3, 4 and 5 represent alternative power supply output stage circuits.

FIG. 6 schematically represents the upper chamber of a one atmosphere glow discharge plasma reactor having a median grid plate.

FIG. 7 represents a graph of voltage, current and power waveforms for a uniform glow discharge plasma.

FIG. 8 represents a graph of voltage, current and power waveforms for a filamentary discharge plasma.

FIG. 9 is a log-log graph of total and plasma power density in milliwatts per cubic centimeter as a function of RMS voltage applied to the electrodes.

FIG. 10 is a log-log graph of total and plasma power density in milliwatts per cubic centimeter, as a function of R.F. frequency.

FIG. 11 is a graph of amplifier frequency and corresponding breakdown current phase angles respective to a particular operating example of the invention.

FIG. 12 is a graph of amplifier frequency and corresponding total reactor power consumption respective to a particular operating example of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to the invention schematic illustrated by FIG. 1, the electrodes **10** are fabricated of copper plate having a representative square plan dimension of 21.6 cm×21.6 cm. Silver soldered to the plates **10** are closed loops **11** of 0.95 cm copper tubing having hose nipples **12** and **13** connected therewith on opposite sides of the closed tubing loop. The edges of the electrode plates should have a radius of curvature comparable to the separation between the electrode plates and median plate to discourage electrical breakdown at the edge of the electrodes. Not shown are fluid flow conduits connected to the inlet nipples **12** for delivering coolant fluid to the loop **11** and to the outlet nipples **13** for recovering such coolant fluid.

The integral metallic units comprising plates **10** and tubing **11** are covered with a high dielectric insulation material **14** on all sides to discourage electrical arcing from the edges or back side of the electrode plates.

Preferably, some mechanism should be provided for adjusting the distance s between plates **10** up to at least 5 cm separation while maintaining relative parallelism. Such a mechanism is represented schematically in FIG. **1** by the rod adjusters **15** secured to the upper and lower plates **10**. This arrangement anticipates a positionally fixed median screen or plate **30**. Although parallelism is used here in the context of parallel planes, it should be understood that the term also comprises non-planar surfaces that are substantially equidistant. Also included are the geometry characteristics of a cylinder having an axis parallel to another cylinder or to a plate.

Energizing the plates **10** is a low impedance, high voltage, R.F. power amplifier **20** having independently variable voltage and frequency capacities over the respective ranges of 1 to at least 9 KV and 1 to 100 KHz. An impedance matching network **31** is connected between the R.F. power amplifier and the electrode plates.

Surrounding the plate assembly is an environmental isolation barrier **21** such as a structural enclosure suitable for maintaining a controlled gas atmosphere in the projected plan volume between the plates **10**. Inlet port **22** is provided to receive an appropriate gas such as air, helium or argon, mixtures of either with air or a mixture of argon with helium. Ambient air may also be used. In any case, gas pressure within the isolation barrier **21** is substantially ambient thereby obviating or reducing the need for gas tight seals. Normally, it is sufficient to maintain a low flow rate of the modified one atmosphere gas through the inlet port **22** that is sufficient to equal the leakage rate. Since the pressure within the isolation barrier **21** is essentially the same as that outside the barrier, no great pressure differential drives the leakage rate. A vent conduit **28** controlled by valve **29** is provided as an air escape channel during initial flushing of the enclosure. Thereafter, the valve **29** may be closed for normal operation.

To broaden the range of operating frequency and other parameters over which the desirable uniform (as opposed to filamentary) glow discharge occurs, an impedance matching network, one embodiment of which is illustrated schematically by FIG. **2**, is added to the power circuit for charging the electrodes **10**. The parameters of this impedance matching network are adjusted for the most stable, uniform operation of the glow discharge. This condition can occur when the reactive power of the plasma reactor is minimized.

FIGS. **3** through **5** represent alternative power supply options having respective attractions. FIG. **3** corresponds to a configuration wherein the bottom electrode terminal T_1 is connected to ground potential and the top terminal T_2 is charged at the full working potential. FIGS. **4** and **5** are electrical equivalents wherein the T_1 and T_2 voltages are 180° out of phase but at only half the maximum potential. FIG. **4** represents a grounded center tap transformer whereas FIG. **5** represents a solid state power circuit embodiment.

Electric fields employed in a one atmosphere, uniform glow discharge plasma reactor are only a few kilovolts per centimeter, values which if D.C. would usually be too low to electrically break down the background gas. Gases such as helium and air will break down under such low electric fields, however, if the positive ion population is trapped between the two parallel or uniformly spaced electrodes, thus greatly increasing their lifetime in the plasma while at the same time the electrons are free to travel to the insulated electrode plates where they recombine or build up a surface charge. The most desirable uniform one atmosphere glow discharge plasma is therefore created when the applied frequency of the RF electric field is high enough to trap the ions between the median screen and an electrode plate, but not so high that the electrons are also trapped during a half cycle of the R.F. voltage. The electrons may be trapped by bipolar electrostatic forces.

If the RF frequency is so low that both the ions and the electrons can reach the boundaries and recombine, the particle lifetimes will be short and the plasma will either not initiate or form a few coarse filamentary discharges between the plates. If the applied frequency is in a narrow band in which the ions oscillate between the median screen and an electrode plate, they do not have time to reach either boundary during a half period of oscillation and are carried for long times. If the more mobile electrons are still able to leave the plasma volume and impinge on the boundary surfaces, then the

desirable uniform plasma is produced. If the applied RF frequency is still higher so that both electrons and ions are trapped in the discharge, then the discharge forms a filamentary plasma.

Without limiting our invention to any particular theory, we are disposed to a relationship between the electrode spacing, the RMS electrode voltage, and the applied frequency which results in trapping ions but not electrons between the two plates, and produces the desired uniform one atmosphere glow discharge plasma. On FIG. 6 is a schematic of the upper chamber of the one atmosphere glow discharge plasma reactor. The lower boundary of this space is the midplane screen or plate, the floating potential of which should remain near ground if the RF power supply output is connected as a push-pull circuit to the two electrodes with a grounded center tap. In the data reported herein, the median screen was grounded through an inductive current choke. In the configuration of FIG. 6, a Cartesian coordinate system is applied as shown, with the applied electric field in the x-direction. The maximum amplitude of the electric field between the grounded median screen and the upper electrode is E_o, and the separation of the screen from the electrodes is the distance d. The median screen, with an exposed sample on it, is assumed not to allow ions through the median plane from the upper chamber to the lower, or vice-versa.

The electric field between the electrodes shown on FIG. 6 is given by

$$E=(E_o \sin \omega t, O, O). \quad (1)$$

It is assumed that the one atmosphere glow discharge operates in a magnetic field free plasma. The equation of motion for the ions or electrons between the two plates is given by a Lorentzian model, in which the electrons and ions collide only with the neutral background gas and, on each collision, give up all the energy they acquired from the RF electric field since the last collision to the neutral gas. The equation of motion for the ions or electrons in the Lorentzian model is given by

$$F=ma=-m\nu_c v-eE, \quad \text{(b 2)}$$

where the first term on the right hand side is the Lorentzian collision term, according to which the momentum mv is lost with each collision that occurs with a collision frequency v_c. The x component of Eq. 2 is given by

$$m\frac{d^2X}{dt^2}+m\nu_c\frac{dx}{dt}=eE_o \sin\omega t, \quad (3)$$

where the electric field E from Eq. 1 has been substituted into the right hand side of Eq. 2. The general solution to Eq. 3 is

$$x=C_1 \sin \omega t=C_2 \cos \omega t, \quad (4)$$

where the constants C_1 and C_2 are given by

$$C_1=-\frac{eE_o}{m}\,\frac{1}{(\omega^2+\nu_c^2)}, \quad (5)$$

and

-continued

$$C_2=-\frac{\nu_c eE_o}{\omega m}\,\frac{1}{(\omega^2+\nu_c^2)} \quad (6)$$

The one atmosphere helium glow discharge is operated at frequencies between $\omega/2\pi=1$ and 30 KHz, where, for helium at one atmosphere,

$$\nu_{ci}\approx 6.8\times 10^9 \text{ ion collisions/sec.}, \quad (7a)$$

and

$$\nu_{ce}\approx 1.8\times 10^{12} \text{ electron coll./sec.} \quad (7b)$$

The collision frequency for ions and electrons given by Eqs. 7a and 7b is much greater than the RF frequency, $V_c>>\omega$. The relation $v_c>>\omega$ for ions and electrons, implies that C_2 is much greater than the constant C_1, or

$$C_2 \approx \frac{eE_o}{m\omega\nu_c}>>C_1 \quad (8)$$

The time dependent position of an ion or an electron in the electric field between the plates is given by substituting Eq. 8 into Eq. 4, to obtain

$$x(t)\approx -\frac{eE_o}{m\omega\nu_c}\cos\omega t. \quad (9)$$

The RMS displacement of the ion or electron during a half cycle is given by

$$x_{rms}=\frac{2}{\pi}\,\frac{eE_o}{m\omega\nu_c}\text{ meters.} \quad (10)$$

If V_o is the driving frequency, in Hertz, then the radian RF frequency is given by

$$\omega=2\pi\nu_o, \quad (11)$$

and the maximum electric field between the plates can be approximated by the maximum voltage V_o appearing between them,

$$E_o=\frac{V_o}{d}=\frac{\pi V_{rms}}{2d}. \quad (12)$$

If the charge in question moves across the discharge width from the median plane to one of the electrode plates during one full cycle, then we may write

$$x_{rms}\leqq\frac{d}{2}. \quad (13)$$

Equation 13 states that the RMS displacement of the particle has to be less than half the clear spacing in order to have a buildup of charge between the plates. In the geometry shown in FIG. 6, the distance d is identified with the distance between the grounded median screen and the energized electrode. Substituting Eqs. 11 to 13 into Eq. 10 yields the relationship

$$\frac{d}{2}\approx\frac{eV_{rms}}{2\pi m\nu_o\nu_c d}. \quad (14)$$

If we now solve for the critical frequency v_o above which charge buildup should occur in the plasma volume, we have—

$$v_o \approx \frac{eV_{rms}}{\pi m v_c d^2} \text{ Hz.} \quad (15)$$

In Eq. 15, the collision frequency v_c is approximately given by Eqs. 7a or 7b for ions or electrons, respectively, at one atmosphere, and the RMS voltage is that which bounds the upper and lower limit of the uniform discharge regime.

The range of parameters over which we have operated a one atmosphere, uniform glow discharge plasma reactor is given in Table I. The nominal pressure at which this discharge has been operated is one atmosphere. The variation of several torr shown in Table I is not intended to represent the day-to-day fluctuations of barometric pressure, but the pressure differential across the midplane screen which is intended to drive active species from the upper plasma through the fabric being exposed. The RMS power shown in Table I is the net power delivered to the plasma, less the reactive power which does not appear in the plasma. The total volume of plasma between the two electrode plates is given by

$$S = 0.93\ d(\text{cm})\text{liters}, \quad (16)$$

where d is the separation of a plate from the median screen in centimeters.

The power densities shown in Table I are far below those of electrical arcs or plasma torches, but also are several orders of magnitude higher than the power densities associated with some other forms of plasma treatment such as corona discharges. The power densities of the one atmosphere glow discharge plasma are generally low enough not to damage exposed fabrics, but are also enough higher than coronal plasmas used for surface treatment that they should provide far more active species than the latter. The plasma parameters, such as electron kinetic temperature and number density are somewhat speculative at this early stage in the development of our invention. A few results from probing the plasma midplane with a floating Langmuir probe indicates that the plasma, without grounding the midplane screen, will float to positive potentials of several hundred volts. The ion kinetic temperatures are very likely close to that of the room temperature atoms with which they frequently collide at these high pressures; the electrons apparently remain numerous and energetic enough to excite the neutral background atoms, hence making this a glow discharge. The existence of excited states which emit visible photons implies that the electron population has a kinetic temperature of at least an electron volt. The diagnostic difficulties of measuring plasma parameters at this high pressure are very severe, since ordinary Langmuir probing technique cannot be applied due to the short mean free paths of the electrons compared to a Debye distance. Electron number densities, however, may be measured by microwave interferometric techniques.

TABLE I

OPERATING CHARACTERISTICS OF THE ONE ATMOSPHERE GLOW DISCHARGE PLASMA REACTOR
working gas = H_e, H_e + 1-7% O_2, Ar, Ar + H_e, Ar + 1-7% O_2, N_2O and atmospheric air
frequency = 1 KHz to 100 KHz
voltage = 1.5-9.5 kV_{rms} plate to plate
electrode gap d = 0.8-3.2 cm
pressure = 760 +15, −5 torr
RMS power = 10 watts to 150 watts
power density = 4-120 mW/cm^3
plasma volume = 0.7-3.1 liters

On FIGS. 7 and 8 are shown two waveforms of voltage and current taken in helium at the same electrode separation and gas flow conditions, but at two different frequencies. FIG. 7 was taken in the uniform glow discharge regime at a frequency of 2.0 kHz, and FIG. 8 was taken in the filamentary discharge regime at a frequency above the uniform plasma operating band at 8.0 kHz. The high output impedance of our RF power supply results in a voltage waveform (trace B) that is very close to sinusoidal. The reactive current waveform (trace C) is interrupted by a breakdown of the plasma twice each cycle, once when the voltage is positive, and once when the voltage is negative. Trace A shows the reactive current waveform at the same voltage and operating conditions, but in air, rather than helium. There was no perceptible plasma present in air under these conditions, and the power is completely reactive. This purely reactive current of trace A was subtracted from the total plasma current in trace C, to yield trace D. The instantaneous power deposited in the plasma (trace E) is found by multiplying the excess plasma current above the reactive current (trace D) by the voltage at that point (trace B). The average power is found by integrating over the duration of the pulses shown, and dividing by this duration. It is in this manner that the power and power density into the plasma were calculated for these highly nonsinusoidal current waveforms. FIGS. 8 for the uniform discharge and 8 for the filamentary discharge show characteristically different power waveforms in trace E; this is a method of distinguishing the uniform from the filamentary discharge.

The plasma power is of interest because it is proportional to the production rate of active species in the plasma; the reactive power is significant because it determines the required power handling rating of the plasma power supply and associated equipment. The total power is the sum of plasma and reactive power. On FIG. 9 is shown a log-log plot of the plasma and total power density in milliwatts per cubic centimeter, as functions of the RMS voltage applied to the parallel plates. The active plasma volume in FIG. 9 was 1.63 liters, with a separation between the median screen and each plate of d=1.75 centimeters in a plasma of helium gas. On FIG. 10 is a similar presentation of the power density plotted on log-log coordinates as a function of the frequency. The approximate bound of the uniform plasma discharge regime is shown by the arrow. These data were taken in helium gas for the same plasma volume and electrode separation as FIG. 10.

EXAMPLE 1

In a first operational example of the invention, the above described physical apparatus sustained a glow discharge plasma in one atmosphere of helium at standard temperature with a separation distance s of 3.0 cm between plates 10. The plates were charged with a 4.4 KV working potential. Holding these parameters constant, the R.F. frequency was increased as an indepen-

dent variable. As the dependent variable, FIG. 11 charts the corresponding breakdown current phase angle. Similarly, FIG. 12 charts the total power, reactive and plasma, used to sustain the plasma at the respective R.F. frequencies.

EXAMPLE 2

In a second operational example of the invention, the above described physical apparatus is used to sustain a glow discharge plasma in one atmosphere of helium at standard temperature with a separation distance s of 1.0 cm between plates 10. In this example, the R.F. frequency was held constant at 30 KHz while plate potential was manipulated as the independent variable and current breakdown phase angle, Θ, (Table 2) and total power, P, (Table 3) measured as dependent variables.

TABLE 2

V(KV)	1	1.5	2	2.5	3	3.5
θ(deg)	28	40	61	46	65	76.5

TABLE 3

V(KV)	1	1.5	2	2.5	3	3.5
P(W)	7	13	22	57	50	44.9

EXAMPLE 3

A third operational example of the invention included a one atmosphere environment of helium between a 1 cm separation distance s between plate electrodes 10 charged at 1.5 KV rms potential. R.F. frequency was manipulated as the independent variable. As a measured dependent variable, Table 4 reports the corresponding phase angle e of breakdown current. The measured dependent variable of Table 5 reports the corresponding total power consumption data, both reactive and plasma.

TABLE 4

f(KHz)	10	20	30	40	50	60	70	80	90	100
θ(deg)	43	32	43	52	54	61	60	56	45	22.5

TABLE 5

f(KHz)	10	20	30	40	50	60	70	80	90	100
P(W)	5	8	11	19	35	43	47	57	89	124

EXAMPLE 4

The largest volume helium plasma of 3.1 liters was achieved with the above described apparatus at a 3.2 cm plate separation having a 5 KV potential charged at 4 KHz.

It will be understood by those of ordinary skill in the art that the present invention is capable of numerous arrangements, modifications and substitutions of parts without departing from the scope of the invention. In particular, FIGS. 3, 4 and 5 represent respective power supply options having respective attractions.

FIGS. 3, 4 and 5 are electrical equivalents wherein the T_1 and T_2 voltages are 180° out of phase but at only half the maximum potential. FIG. 4 represents a grounded center top transformer whereas FIG. 5 represents a solid state power circuit embodiment with or without a provision for a grounded center tap of the output.

Although expansive data is not presently available, it is to be noted that a uniform glow discharge plasma has been sustained by the FIG. 1 apparatus with a one atmosphere ambient air environment and 8 KV/cm R.F. electric field.

Having fully disclosed our invention, the presently preferred embodiments and best modes of practice,

We claim:

1. Apparatus to generate and maintain a glow discharge plasma at a pressure of about 1 atmosphere, the apparatus comprising

a pair of electrically insulated electrodes aligned and secured in equidistant opposition,

means for supplying and maintaining a glow discharge plasma sustaining gas at a pressure of about one atmosphere in the volumetric space between said electrodes, and

radio frequency (RF) amplifier means for generating and maintaining a glow discharge plasma by energizing said electrodes with a potential of 1 to at least 5 kV rms at 1 to 100 kHz, wherein said radio frequency amplifier means includes an impedance matching network.

2. An apparatus as described in claim 1 wherein said radio frequency amplifier means for generating and maintaining a glow discharge plasma comprises means for providing an applied frequency of the RF electric field which is high enough to trap the positive ions of the plasma between the electrodes, but not so high that the electrons of the plasma are also trapped during a half cycle of the RF voltage.

3. An apparatus as described by claim 2 which comprises means for establishing and maintaining a gas barrier envelope surrounding said plates and the volumetric space therebetween.

4. An apparatus as described by claim 2 wherein said means for supplying and maintaining the gas comprises gas supply means to provide a substantially steady supply flow of said gas.

5. An apparatus as described by claim 2 wherein said gas is helium.

6. An apparatus as described by claim 2 wherein said gas is a mixture of helium and air.

7. An apparatus as described by claim 2 wherein said gas is argon.

8. An apparatus as described by claim 2 wherein said gas is a mixture of argon and air.

9. An apparatus as described by claim 2 wherein said gas is a mixture of argon and helium.

10. An apparatus as described by claim 2 wherein said gas is atmospheric air.

11. An apparatus as described by claim 2 wherein said gas is nitrous oxide.

12. An apparatus as described by claim 2 wherein said electrodes are fluid cooled.

13. An apparatus as described by claim 12 wherein fluid flow conduits are bonded to said electrodes to extract heat from said electrodes.

14. A method of generating and maintaining a uniform glow discharge plasma at a pressure of about 1 atmosphere within a volumetric space between two electrodes energized by radio frequency amplifier means having an impedance matching network, said method comprising the steps of operating said amplifier means to energize said electrodes with a potential of 1 to at least 5 kV rms at 1 to 100 kHz frequency while charging and maintaining the volumetric space between said electrodes with a glow discharge plasma sustaining gas at approximately 1 atmosphere of pressure.

15. The method as described in claim 14 wherein the uniform glow discharge plasma is generated and maintained by using an applied frequency of the RF electric field which is high enough to trap the positive ions of the plasma between the electrodes, but not so high that the electrons of the plasma are also trapped during a half cycle of the RF voltage.

16. A method as described by claim 15 wherein said electrodes are enclosed by an environmental gas barrier internally charged by a substantially continuous flow of said gas.

17. A method as described by claim 16 wherein said gas is helium.

18. A method as described by claim 16 wherein said gas is a mixture of helium and air.

19. A method as described by claim 16 wherein said gas is argon.

20. A method as described by claim 16 wherein said gas is a mixture of argon and air.

21. A method as described by claim 16 wherein said gas is a mixture comprising helium and argon.

22. A method as described by claim 15 wherein said gas is atmospheric air.

23. A method as described by claim 14 wherein said gas is nitrous oxide.

24. A method as described by claim 15 wherein said electrodes are positioned at a separation distance therebetween of 5 cm or less.

25. A method as described by claim 24 wherein at least one of said electrodes is positionally adjustable relative to the other.

26. A method as described by claim 15 wherein said amplifier frequency is variable over the range of 1 to 100 KHz.

27. A method as described by claim 15 wherein said amplifier potential is variable over the range of 1 to at least 5 kV rms.

* * * * *

APPENDIX B

Patent Disclosures

APPENDIX B

DISCLOSURE OF INVENTION - #1

Inventor: John Reece Roth, Ph.D., Professor of Electrical Engineering

Title: Method and Apparatus for Covering the Surface of Aircraft and Ships with a Uniform Glow Discharge Plasma.

Purpose of Invention: This disclosure describes a method for covering the surface of aircraft and ships with a steady-state, uniform, glow discharge plasma operating in atmospheric air or other gases at one atmosphere of pressure. Such a layer of plasma may have utility in protecting military ships and aircraft from interrogation by hostile radar; in protecting such vehicles against an electromagnetic pulse (EMP) or high power directed electromagnetic energy weapons; and in reducing drag and otherwise improving the aerodynamic characteristics of the atmospheric boundary layer on vehicles by reducing turbulence and the formation and shedding of turbulent vortices.

Physical Mechanism of the Invention; It is proposed to apply the previously disclosed mechanism for generating a one atmosphere steady state uniform glow discharge in atmospheric air and other gases in a parallel plate industrial plasma reactor, and to extend this mechanism to the formation of a plasma layer on the skin of aircraft and naval ships. We propose to cover the metallic skin of aircraft or ships with an insulating layer, such as paint, epoxy, flame-sprayed ceramic, or some other appropriate insulating surface covering, and then to energize the metallic skin of the ship or aircraft with a low frequency, high voltage RF signal with respect to an infinite ground plane, with a sufficiently high voltage to generate electric fields near the surface of the vehicle of more than approximately 10 KV RMS per centimeter. The frequency of the RF signal should range from a few hundred hertz up to 30 KHz, but in any case be sufficiently high that ions generated in the plasma above the layer of surface insulation do not have time during a half cycle of oscillation to impact the surface of the vehicle. It is anticipated that operation in this manner will produce a layer several centimeters thick of uniform, glow discharge plasma, just as it does in the previously disclosed parallel plate industrial plasma reactor.

The principal difference between the one atmosphere parallel plate industrial plasma reactor and the vehicle plasma is the method of generating the RF electric field above the surface of the vehicle. Modifications of the parallel plate arrangement are necessary in a freely moving vehicle in the atmosphere or on the surface of the sea, to provide a grounded reference plane which will make it possible to sustain electric fields near the surface of the vehicle in excess of approximately 10 KV per centimeter, needed to produce a uniform glow discharge at one atmosphere in air or other gases.

In the case of aircraft, we suggest that one electrode be the skin of the aircraft, coated with an insulating dielectric coating. The other electrode, in the case of aircraft, may be provided in one of several ways. One method, suggested in a private conversation by Dr. Robert J. Barker, is to locate a high porosity screen a few centimeters away from the skin of the aircraft to serve as a parallel electrode, much in the manner of the parallel plate one atmosphere glow discharge industrial plasma reactor. A gridwork of fine wires would establish the necessary electrostatic potential while still permitting the boundary layer and incident electromagnetic radiation to interact with the layer of plasma on the surface. The delicacy and drag of such a fine gridwork, however, have obvious potential disadvantages, and lead us to suggest a number of other possibilities. A second possibility is to drag behind the aircraft a bare trailing wire, the function of which is to provide a conduit for

flow of charge from the aircraft to the surrounding atmosphere, and thus establish the surrounding atmosphere as a "grounded" or neutralizing electrode. A third possiblility is to use the partial ionization of the engine exhaust of an aircraft to serve the same function as the trailing wire just discussed; by insulating the aircraft engines from the rest of the aircraft, or by surrounding the exhaust jet with a circular biasing electrode, it should be possibe to use the electrical conductivity of the engine exhaust as a reference electrode to establish a potential difference with the surrounding atmosphere. A fourth possibility for establishing an electric field at the surface of the skin of an aircraft is to electrically isolate major portions of the aircaft from each other, and apply the RF driving voltage between these portions of the aircraft. For example, the aircraft wings could be electrically isolated from the fuselage, and the RF power supply connected between the wings and fuselage. An alternative arrangement might be to have the forward part of the aircraft electrically isolated from the aft portion of the aircraft, and the electrical power supply connected between those parts. A fifth possibility is to have the ventral surface of the aircraft electrically isolated from the dorsal surface, and the RF power supply connected between them.

In addition to the electrode configurations discussed above, the electrodes used to create the one atmosphere glow discharge plasma can arranged in parallel strips insulated from the vehicle surface and each other, and possibly the surrounding atmosphere, on the surface of the aircraft or other vehicle, with adjacent strips being operated at radio frequency voltages 180° out of phase with each other, and at sufficiently high RF voltages that RMS electric fields of 10 kilovolts per centimeter are generated approximately 1 centimeter above the surace of the vehicle. The width of the individual strip electrodes should be wide enough to create a uniform plasma layer over the surface of the vehicle. The strip electrodes can be oriented on the surface of the vehicle as a matter of convenience, in a quasi-parallel pattern, or the electrodes might be placed parallel or perpendicular to the aerodynamic velocity vector of the gas in the boundary layer flowing over the surface of the vehicle. The width of individual strip electrodes may be adjusted over the surface of the aircraft, in such a way as to produce dense plasma where it is most needed, and more rarefied plasma where that is satisfactory for the intended application of the plasma layer.

In application to ships, a plasma could be established in the same manner as described above, that is by coating the surface of the ship with an insulating layer, and then, a few centimeters away from the surface, a fine gridwork of wires to establish an electrode plane several centimeters from the surface of the ship. Again, the delicacy and inconvenience of such a network of fine wires on the surface of an ocean-going vessel has obvious practical difficulties. A second mechanism for providing strong electric fields above the surface of a ship would be to use the sea as one electrode, and since the metal surface of the hull would be coated with an insulating coating in any case, the entire ship could be driven by an RF voltage applied between the hull and an electrode in contact with the surrounding sea. A third possibility, if the electrical conductivity of the sea is insufficient, might be to seed the ship's wake with an alkali metal salt to increase its conductivity, and use this high conductivity wake as the reference electrode for RF excitation.

Apparatus Required - The apparatus required to generate a one atmosphere glow discharge plasma around vehicles in the atmosphere or in the sea is indicated schematically on Figure 1. A low frequency RF power supply capable of operating from a few hundred hertz to 10 KHz at RMS voltages up to 20 KV is connected to the fuselage or hull of the vehicle to be energized, and the other RF terminal connected to a reference electrode, as discussed above. These connections are made through an impedance matching network, the function of which is to minimize the reactive power in the RF

circuit. The fuselage or hull of the vehicle may be coated with an electrically insulating coating, if necessary.

Previously reported measurements on a parallel plate uniform glow discharge plasma reactor operating at atmospheric pressure indicated that such glow discharges could be maintained by average power densities ranging from below 10 milliwatts per cubic centimeter to values higher than 100 milliwatts per cubic centimeter. On the basis of these experiments, it is reasonable to suppose that a power density of 50 milliwatts per cubic centimeter may be required to maintain a layer of plasma surrounding an aircraft. If the aircraft has a total surface area of 500 square meters, and if the layer of plasma is two centimeters thick, 10 cubic meters of plasma would need to be generated at 50 milliwatts per cubic centimeter. This would require an energy input to generate such a plasma of 500 KW, a power level about one percent of the total shaft horsepower generated by the jet engines of typical aircraft. Thus, there appears to be no reason, on energetic grounds, why full-scale aircraft should not be able to supply the power requirements for generating such a uniform plasma over their surface, at an energy cost in shaft horsepower that is only a few percent of that developed for their flight requirements. Even in an extreme case, the mass of the electrical power generator and power supplies required to produce the high voltage RF needed to produce the plasma should require no more than about 1 kilogram per kilowatt, thus burdening the aircraft in the example above with no more than about 500 kilograms of additional equipment. In practice, this is likely to be a very generous overestimate of the mass of a single unit generating half a megawatt of electrical and RF power.

Claims

Claim #1 - We claim to have suggested an apparatus and method for generating a steady state uniform one atmosphere glow discharge on the surface of ships at sea.

Claim #2 - We claim to have described an apparatus and method for producing a steady state, uniform glow discharge at one atmosphere pressure in atmospheric air on the surface of aircraft flying through the atmosphere.

Claim #3 - We have disclosed several methods for providing a reference electrode for the application of a high RF potential to the surface of an aircraft.

Claim #4 - We have disclosed several methods for establishing a reference electrode for the application of high RF voltages to the insulated hull of a ship.

DISCLOSURE OF INVENTION - #2

Inventor: John Reece Roth, Ph.D., Professor of Electrical Engineering

Title: Method and Apparatus for Reducing the Aerodynamic Drag of Aircraft and Other High-Speed Vehicles in the Atmosphere

Purpose of Invention: This disclosure describes a method for covering the surface of aircraft, ships, or other vehicles moving in the atmosphere with a steady state, uniform, glow discharge plasma for the purpose of reducing their aerodynamic drag. Such a layer of plasma is capable of producing an electrostatic body force on the aerodynamic boundary layer. Such a body force may reduce the level of boundary layer turbulence and/or suppress the formation of turbulent vortices, thus reducing the drag coefficient of the aircraft in the atmosphere, and eliminating other consequences of turbulence in the boundary layer above the skin of the aircraft, including aerodynamic noise.

Physical Mechanism of the Invention: It is proposed to utilize the previously disclosed mechanism for the formation of a plasma layer on the skin of aircraft, naval ships, or other high speed vehicles which move in the atmosphere. This mechanism should generate a layer a few centimeters thick of steady state, uniform, glow discharge plasma immediately above the surface, as a consequence of establishing an RF electric field near the surface of the vehicle with an RMS amplitude of at least 10 KV per centimeter, and with a frequency which might range from 0.5 to 50 KHz, depending on operating conditions. Several different arrangements for implementing such conditions near the surface of a vehicle moving in the atmosphere have been disclosed previously. The purpose of these strong RF electric fields is to increase the lifetime of ions generated by electron impact in the boundary layer above the surface of the vehicle. The ions are expected to oscillate above the surface, without having the time or opportunity during each half cycle to either impact the vehicle, or to escape from the region of strong electric field near the surface of the vehicle. The trapping of positive ions by the RF alternating electric field will form a plasma, since ambipolar forces will attract the necessary electrons. Such a centimeters-thick layer of plasma has been experimentally observed in the laboratory between two parallel plates in an atmospheric parallel plate glow discharge plasma reactor.

The principal difference between the one atmosphere parallel plate industrial plasma reactor and the vehicle plasma is the method of generating the RF electric field above the surface of the vehicle. Modifications of the previously disclosed parallel plate arrangement are obviously necessary in a three dimensional, freely moving vehicle in the atmosphere or on the surface of the sea, to provide a grounded reference plane. Such a plane will make it possible to sustain electric fields near the surface of the vehicle in excess of approximately 10 KV per centimeter RMS, which are needed to produce a uniform glow discharge at one atmosphere in air or other gases.

Apparatus Required: Previously reported measurements on a parallel plate uniform glow discharge plasma reactor operating at atmospheric pressure indicated that such glow discharges could be maintained by average power densities ranging from below 10 milliwatts per cubic centimeter to values higher than 100 milliwatts per cubic centimeter. On the basis of these experiments, it is reasonable to suppose that a power density of 50 milliwatts per cubic centimeter may be required to maintain a layer of plasma surrounding an aircraft. If the aircraft has a total surface area of 500 square meters, and if the layer of plasma is two centimeters thick, 10 cubic meters of plasma would need to be generated at 50 milliwatts per cubic centimeter. This would

require an energy input to generate such a plasma of 500 KW, a power level of about one percent of the total shaft horsepower generated by the jet engines of typical aircraft. Thus, there appears to be no reason, on energetic grounds, why full-scale aircraft should not be able to supply the power requirements for generating such a uniform plasma over their surface, at an energy cost in shaft horsepower that is only a few percent of that developed for their flight requirements. Even in an extreme case, the mass of the electrical power generator and power supplies required to generate the high voltage RF needed to produce the plasma should require no more than about 1 kilogram per kilowatt, thus burdening the aircraft in the example above with no more than about 500 kilograms of additional equipment. In practice, this is likely to be a very generous overestimate of the mass of a single unit generating half a megawatt of electrical and RF power.

By turning the plasma on and off, and varying the intensity of the plasma through the input power density and the applied RF voltage, it should be possible to vary the drag coefficient of the aircraft from the normal value without the plasma layer, to values which may be much lower than those normally encountered. The plasma would tend to be swept along with the aerodynamic boundary layer flow, and would tend to accumulate in areas of stagnation or in vortices, thus making these aerodynamically drag-producing structures subject to an electric field, which may be manipulated by auxiliary or control electrodes on the surface of the aircraft.

In addition to reducing the drag and manipulating the geometry and position of vortices and areas of stagnant aerodynamic flow, the boundary layer may be either speeded up or slowed down by traveling electrostatic (peristaltic) waves, in which regions of higher than average electric field are caused to flow over the surface of the aircraft in the direction of the aerodynamic flow, thus exerting an electrostatic body force on the aerodynamic flow in the boundary layer, speeding it up, and further reducing the drag coefficient between the aircraft and the surrounding atmosphere. The induction of peristaltic waves of plasma and/or neutral boundary gases can be accomplished by covering the surface of the aircraft not with a single electrode as previously disclosed, but with a series of insulated strip electrodes, oriented perpendicular to the normal aerodynamic flow of the boundary layer gases over the aircraft. These strip electrodes could then be energized in sequence, to exert an acceleration of the plasma in the boundary layer, thus making the flow more laminar, and discouraging the formation of vorticity.

The electrodes used to create the one atmosphere glow discharge plasma can be arranged in parallel strips on the surface of the aircraft or other vehicle with adjacent strips being operated at radio frequency voltages 180° out of phase with each other, and at sufficiently high RF voltages that RMS electric fields of 10 kilovolts per centimeter are generated approximately 1 centimeter above the surface of the vehicle. The width of the individual strip electrodes should be wide enough to create a uniform plasma layer over the surface of the vehicle. The strip electrodes can be oriented on the surface of the vehicle as a matter of convenience, in a quasi-parallel pattern, or the electrodes might be placed parallel or perpendicular to the velocity vector of the gas in the boundary layer flowing over the surface of the vehicle. The width of individual strip electrodes can be adjusted over the surface of the aircraft, in such a way as to produce dense plasma where it is most needed, and more rarefied plasma where that is satisfactory for the intended application of the plasma layer.

In the same way just described, the phasing of the RF voltage on adjacent parallel electrodes could be adjusted to decelerate as well as accelerate the boundary layer, thus producing a braking effect on the motion of the aircraft through the atmosphere.

Various elaborations of this plasma-related boundary layer control can be envisioned. The surface of the aircraft or vehicle might be fitted with a series of parallel insulated electrodes, the

contours of which are perpendicular to the most laminar and least turbulence-producing boundary layer flow over the aircraft, as determined by wind tunnel tests. Phased excitation of these contoured parallel insulated electrodes could provide a body force accelerating the boundary layer flow over the aircraft in a direction which is least likely to lead to turbulence and vortex formation. Such manipulation of the boundary layer by electrostatic body forces may, in addition, have the effect of raising the Reynolds number for transition to turbulent flow both locally, and for the aircraft or vehicle as a whole.

CLAIMS

Claim #1 - We have suggested a method for decreasing the drag coefficient and the production of vorticity on aircraft and other vehicles moving at high velocity through the atmosphere which uses a uniform steady state one atmosphere glow discharge plasma generated by low frequency RF power.

Claim #2 - We claim to have described a method for using the electrostatic body force in a one atmosphere uniform glow discharge plasma to accelerate the boundary layer on the surface of an aircraft or other vehicle by sequential and peristaltic excitation of insulated electrode strips located on the surface of the aircraft.

Claim #3 - We claim to have described a method for decelerating the boundary layer on the surface of aircraft or other vehicles moving in the atmosphere using sequential or peristaltic excitation of insulated electrode strips oriented at right angles to the flow direction of the boundary layer and located on the surface of the aircraft.

Claim #4 - We claim to have described a method for guiding the boundary layer flow on the surface of an aircraft in directions which minimize drag and vorticity by covering the surface of the aircraft with insulated strip electrodes which are sequentially or peristaltically excited in such a way that the electrostatic body force on the surface plasma accelerates it in directions which minimize the turbulence, aerodynamic drag, and vortex formation.

Claim #5 - We have disclosed a method by which ice can be prevented from forming on the surface of aircraft by the excitation of a surface layer of plasma at sufficiently high power levels to melt any ice between insulated electrodes attached to the aircraft fuselage and the plasma containing boundary layer.

Claim #6 - We have disclosed a method by which aircraft can be made visible at night for purposes of safety or traffic control by covering their surfaces with a one atmosphere uniform glow discharge plasma.

DISCLOSURE OF INVENTION - #3

Inventor: John Reece Roth, Ph.D., Professor of Electrical Engineering

Title: Method and Apparatus for Plasma Cloaking of Aircraft, Ships, and other Military Targets in the Atmosphere.

Purpose of Invention: This disclosure describes a method of passive plasma cloaking of military targets in the atmosphere which utilizes a uniform surface layer of one atmosphere glow discharge plasma generated by low frequency RF fields. Such a layer of plasma could simultaneously serve several objectives. It could provide a protective layer against high power directed electromagnetic energy weapons, since, at many wavelengths, a plasma is a far stronger absorber than an equivalent thickness of neutral atmosphere. Such a plasma layer could also serve as a shield against an electromagnetic pulse designed to damage or disable receivers and sensitive electronic equipment on the target. Such a layer could further serve to absorb, scatter, or reflect in other directions radar pulses interrogating the target from ground-based radar or radar guided weapons.

Physical Mechanism of the Invention: It is proposed to apply the previously disclosed mechanism for generating a plasma layer on the surface of high speed aircraft or other vehicles moving through the atmosphere by generating a steady state uniform glow discharge plasma layer around the vehicle. The plasma layer would be formed by applying a low frequency RF electric field, between 0.5 and 50 KHz, to insulated electrodes on the surface of the aircraft using voltages high enough to produce RMS electric fields of at least 10 kilovolts per centimeter, a centimeter or two above the surface of the vehicle.

The interaction of incident electromagnetic radiation with the plasma layer, and the cloaking effect of the plasma layer would result from the characteristically strong interaction between the incident RF electromagnetic field, and the plasma electron population. Strong attenuation of incident electromagnetic signals would be anticipated as a result of the very high electron-neutral collision frequencies at one atmosphere, frequencies that are characteristically in the terahertz range. In addition to attenuation, other plasma-electromagnetic interactions would occur, depending on whether the incident radiation is above or below the electron plasma frequency of the plasma layer. Electron number densities in the plasma layer at one atmosphere are anticipated to be 10^{12} electrons per cubic centimeter or higher. Such number densities would lead to strong interactions with all microwave and RF frequencies below approximately 9 GHz.

It is anticipated that the electron plasma frequency for the plasma layer can be adjusted by increasing or decreasing the electron number density through control of the power density dissipated in the plasma layer. Thus, by increasing or decreasing the power density dissipated in the plasma layer, the electron plasma frequency can be adjusted in such a way as to be above the highest anticipated probing frequency used by a potential adversary. Such a plasma layer can be maintained at relatively small cost in energy, power densities from 10 to 100 milliwatts per cubic centimeter having been typical in related laboratory experiments on a parallel plate one atmosphere glow discharge plasma reactor. The plasma layer is a passive cloaking mechanism, since once it is turned on, it provides continuous protection against probing electromagnetic radiation up to frequencies at least equal to the electron plasma frequency in the surface plasma layer, and possibly beyond. The pulsed energy load dumped in the plasma layer in the case of directed electromagnetic

energy weapons or an electromagnetic pulse (EMP) may be convected away by the aerodynamic gas flow over the surface of the aircraft or other vehicle as it moves through the atmosphere.

Apparatus Required: The apparatus required to create a uniform steady state glow discharge plasma in atmospheric air on ships and aircraft has been previously disclosed. This apparatus includes insulated electrodes on the surface of the vehicle, energized by an RF power supply capable of operating from 0.5 to 50 KHz, and capable of producing sufficiently high RMS voltages on the insulated surface electrodes to generate an RMS electric field of 10 KV per centimeter approximately 1 centimeter above the surface of the aircraft.

Previously reported measurements on a parallel plate uniform glow discharge plasma reactor operating at atmospheric pressure indicated that such glow discharges could be maintained by average power densities ranging from below 10 milliwatts per cubic centimeter to values higher than 100 milliwatts per cubic centimeter. On the basis of these experiments, it is reasonable to suppose that a power level of 50 milliwatts per cubic centimeter may be required to maintain a layer of plasma surrounding an aircraft. If the aircraft has a total surface area of 500 square meters, and if the layer of plasma is two centimeters thick, 10 cubic meters of plasma would need to be generated at 50 milliwatts per cubic centimeter. This would require an energy input to generate such a plasma of 500 KW, a power level of about one percent of the total shaft horsepower generated by the jet engines of typical aircraft. Thus, there appears to be no reason, on energetic grounds, why full-scale aircraft should not be able to supply the power requirements for generating such a uniform plasma over their surface, at an energy cost in shaft horsepower that is only a few percent of that developed for their flight requirements. Even in an extreme case, the mass of the electrical power generator and power supplies required to produce the high voltage RF needed to produce the plasma should require no more than about 1 kilogram per kilowatt, thus burdening the aircraft in the example above with no more than about 500 kilograms of additional equipment. In practice, this is likely to be a very generous overestimate of the mass of a single unit generating half a megawatt of electrical and RF power.

CLAIMS

Claim #1: We claim to have suggested an apparatus and method for the plasma cloaking of aircraft and other vehicles operating in the atmosphere by utilizing a one atmosphere uniform steady state glow discharge plasma generated with low frequency RF power applied to insulated electrodes on the surface of the vehicle.

Claim #2: We claim to have described an apparatus and method that can be used to protect military targets operating in the atmosphere against electromagnetic pulse (EMP), by absorbing the energy of the electromagnetic pulse in a surface layer of plasma surrounding the vehicle.

Claim #3: We claim to have described an apparatus and method for protecting military targets operating in the atmosphere against directed microwave energy weapons by surrounding such targets with a layer of plasma, the densities of which are sufficiently high to interact strongly with the incident electromagnetic radiation.

Claim #4: We claim to have described an apparatus and method for the cloaking of military targets operating in the atmosphere against interrogation by radar guided weapons, by scattering, absorbing, or refracting radar pulses from such hostile weapons, using a layer of plasma above the surface of the aircraft or vehicle.

Claim #5: We claim to have described an apparatus and method for cloaking military radar targets against interrogation by hostile radar, as the result of absorption, scattering or refraction of the incident radar pulses from a plasma layer surrounding the target.

APPENDIX C

Abstracts of Conference Presentations

36th Annual Meeting, APS Division of Plasma Physics
7–11 November 1994—Minneapolis, MN

Applications of the One Atmosphere Glow Discharge Plasma to Illumination and Aerodynamic Boundary Layer Control* **C. LIU AND J. R. ROTH,** UTK Plasma Science Laboratory, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, TN 37996-2100.--
A one-Atmosphere, steady-state, uniform glow discharge plasma that covers the surface of a free-standing body has recently been operated in air, helium, and other gases at the UTK Plasma Science Laboratory[1]. In this paper we will report exploratory measurements on two potential applications of this plasma source: using the electrostatic body force on this layer of plasma to effect boundary layer control on the surface of aircraft; and as a new source of illumination, which uses the surface layer of steady-state uniform glow discharge plasma to excite fluorescence on a phosphor below the plasma layer. This lighting source would be safer and cause less environmental impact than lighting devices which require mercury, and must be operated at low pressure.

[1]Liu, Chaoyu and Roth, J. R., "An Atmospheric Glow Discharge Plasma For Aerodynamic Boundary Layer Control". Proc. 1994 International Conference on Plasma Science, IEEE Cat., #94CH3465-2, (1994. 97-97.

Abstract Submitted for the
22nd IEEE International Conference
on Plasma Science

June 5-8 1995
Madison, Wisconsin, USA

BOUNDARY LAYER CONTROL BY A ONE ATMOSPHERE UNIFORM GLOW DISCHARGE PLASMA LAYER*

Chaoyu Liu and J. Reece Roth
UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, TN 37996-2100

ABSTRACT

At the University of Tennessee's Plasma Science Laboratory, we have recently developed, with AFOSR support, a new type of uniform glow discharge plasma which is capable of operating at one atmosphere in air and other gases.[1] This plasma is neither a corona discharge nor a filamentary (ozonizer) discharge, the more familiar plasma discharges also capable of operating at one atmosphere. The physical processes which make this discharge possible, based on an RF ion trapping mechanism, will be described theoretically, and the RF frequency, electric field, and electrode separation required to maintain this discharge will be derived from first principles. Characteristic operating and plasma parameters in air at one atmosphere are: RF frequency, 1-6 kHz, RMS electric field $\approx$ 9 kV/cm; maximum RMS voltage $\approx$ 4 kV; plasma number density $\approx 10^{10}$ electrons/cm^3; and input power density 10-200 milliwatts/cm^3. The maximum volume of uniform plasma generated to date has been 2.8 liters between parallel plates.

More recently, the parallel plate geometry described above has been geometrically transformed and made to operate on a planar surface, producing a steady-state plasma layer up to several millimeters thick. The electric field in this surface plasma layer can provide a body force per unit area of up to perhaps several thousand pascals. Some speculative applications to boundary layer control, turbulence suppression, drag reduction and noise reduction will be put forward.

---

*Supported in part by AFOSR contract F49620-94-10249 (Roth).

1. J. R. Roth, C. Liu, and M. Laroussi: "Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure". Proc. IEEE International Conf. on Plasma Science, ISBN0-7803-0716-X (1992) pp. 170-171.

APPENDIX D

Poster Materials

Paper 8P-23

Applications of the One Atmosphere Glow Discharge Plasma to Illumination and Aerodyynamic Boundary Layer Control

Chaoyu Liu and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2100, USA
Telephone: (615) 974-4446

Presented at the 36th Annual Meeting, APS Division of Plasma Physics
7-11 November 1994, Minneapolis, MN.
APS Bulletin, Vol. 39, No. 7, November, 1994. P.1730

* Research supported by AFOSR contract F49620-94-10249(Roth).

D-1

Applications of the One Atmosphere Glow Discharge Plasma to Illumination and Aerodynamic Boundary Layer Control*, Chaoyu Liu and J.R.Roth; UTK Plasma Science Laboratory, Univ. of Tennessee, Knoxville, TN. 37996-2100. A One-Atmosphere, steady-state, uniform glow discharge plasma that covers the surface of a free-standing body has recently been operated in air, helium, and other gases at the UTK Plasma Science Laboratory[1]. Several different configurations of possible commercial interest have been developed, in addition to the original uniform glow discharge plasma between two insulated, parallel electrodes at one atmosphere[2]. In this paper we will report exploratory measurements on two potential applications of this plasma source: using the electrostatic body force on this surface layer of plasma to effect boundary layer control on the surface of aircraft; and as a new method of illumination, which uses the surface layer of the steady-state uniform glow discharge plasma to excite fluorescence on a surface layer of phosphor below the plasma layer. This new lighting source would be safer

and cause less environmental impact than lighting devices which require mercury, and must be operated at low pressure. Other studies of the characteristics of this one atmosphere, steady-state, uniform glow discharge plasma also will be reported.

12

*** Research supported by AFOSR contract F49620-94-10249(Roth).**

---

[1]. Liu, Chaoyu and Roth, J. R., An Atmospheric Glow Discharge Plasma For Aerodynamic Boundary Layer Control. 1994 IEEE International Conference on Plasma Science, Santa Fe, New Mexico, June 6-8, 1994, IEEE Cat, #94CH3465-2, (1994)PP. 97-98.

[2]. Roth, J. R.; Liu, C.; and Laroussi, M.: Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure. 1992 IEEE International Conference On Plasma Science, Tampa, FL, June 1-3, 1992, IEEE Cat, #92TH0460-6, (1992)pp. 170-171.

OBJECTIVES

1. **Designing and creating a layer of steady-state, uniform glow discharge plasma on the surface of a metal or insulator; which can be used to effect boundary layer control on the surface of aircraft; or as a new source of fluorescent illumination.**

2. **Operating this free-standing steady-state, uniform glow discharge plasma at one atmosphere pressure in several working gases, including in air.**

3. **Laboratory experiments using the surface layer of a one atmosphere pressure steady-state uniform glow discharge plasma to excite fluorescence on a phosphor near the plasma layer. This lighting source potentially could be safer and cause less environmental impact than normal lighting devices.**

4. **Theoretical and exploratory experimental study of this high pressure discharge plasma and its other industrial applications.**

CREATING A LAYER OF STEADY-STATE, UNIFORM GLOW DISCHARGE PLASMA ON THE SURFACE OF A METAL OR INSULATOR

- Several different configurations of the one atmosphere uniform glow discharge plasma generators have been developed[1] .
- We extend the previously-developed configurations of one atmosphere uniform glow discharge plasma generators to include a conducting or insulating base. Such plasma surface layers can be applied to a simulated aircraft fuselage, or a new generation of lighting sources.

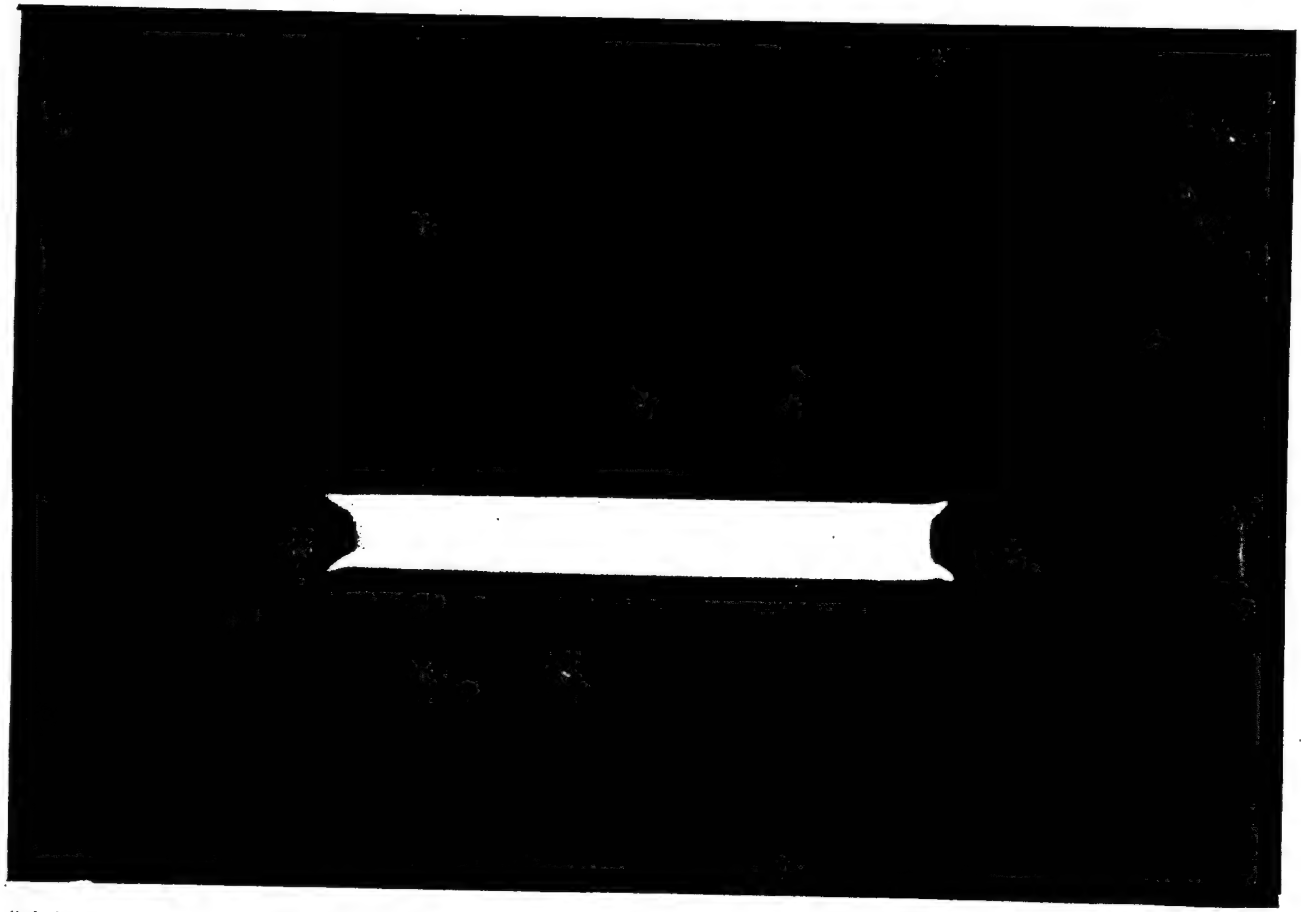


Fig. 1. Photograph of the original parallel plate one atmosphere uniform glow discharge plasma generator in the UTK Plasma Science Laboratory.

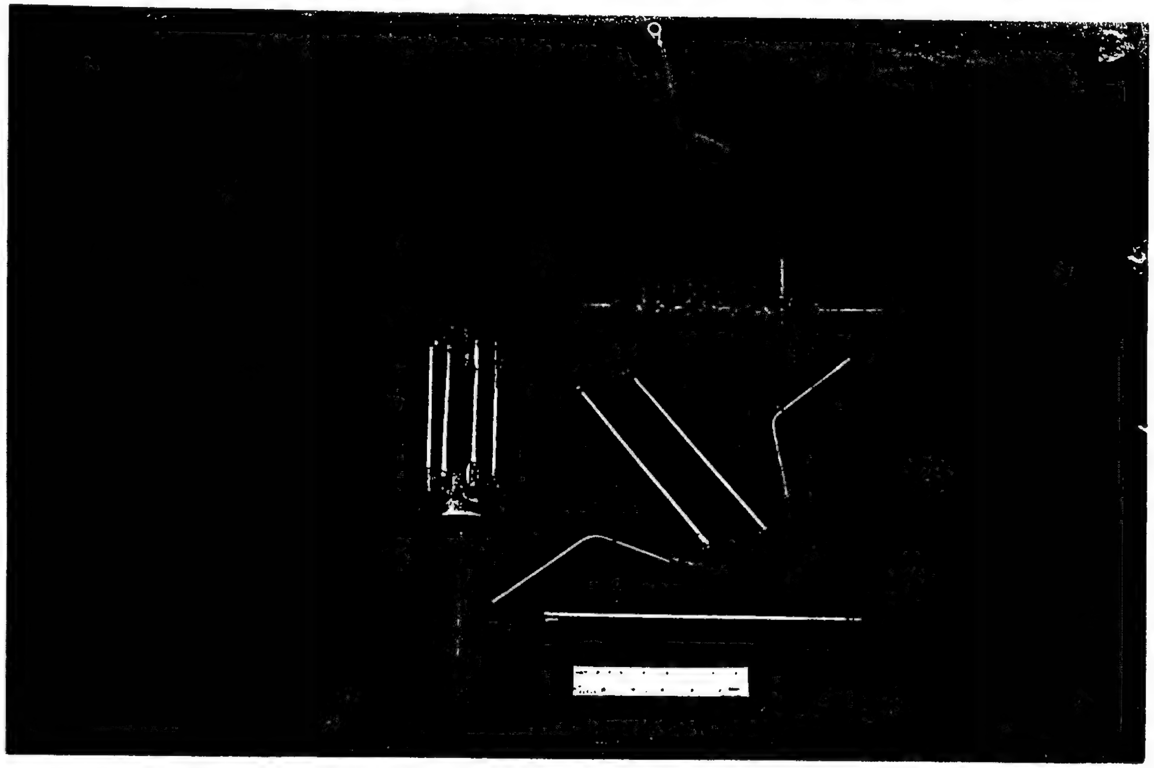


Fig. 2. Photograph of several configurations of one atmosphere uniform glow discharge plasma generators.

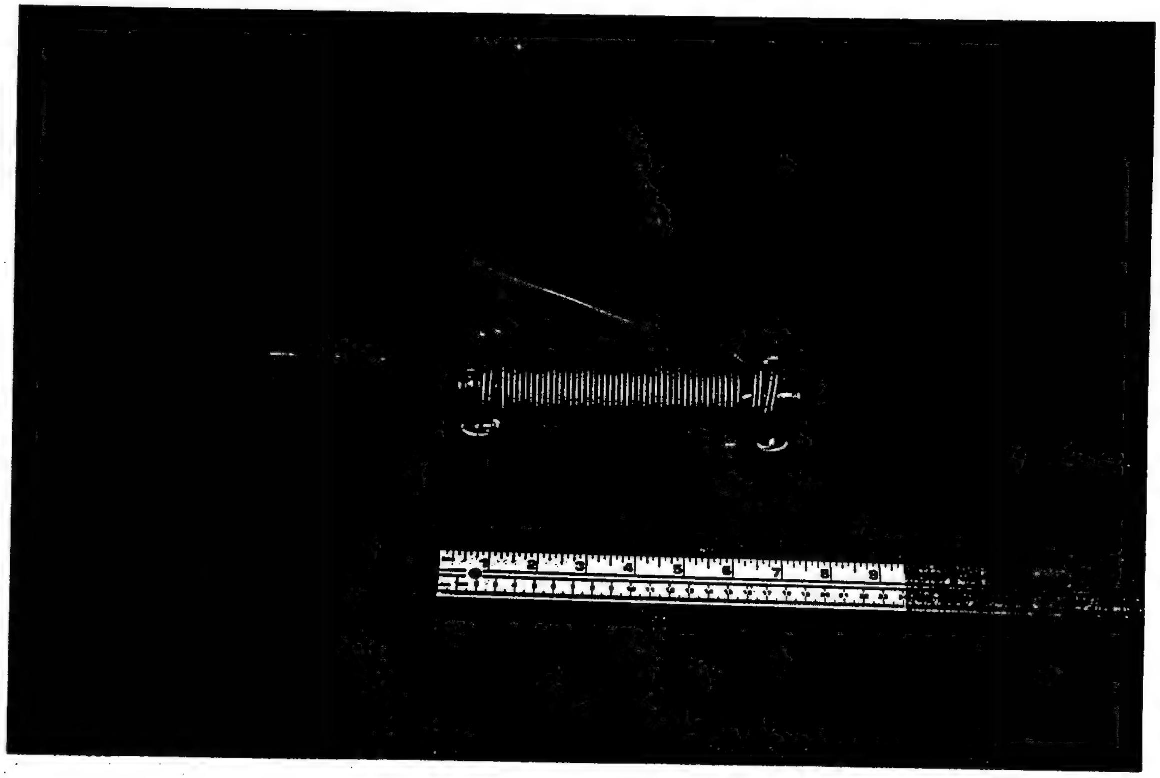


Fig. 3. The new metal base surface layer plasma generator.

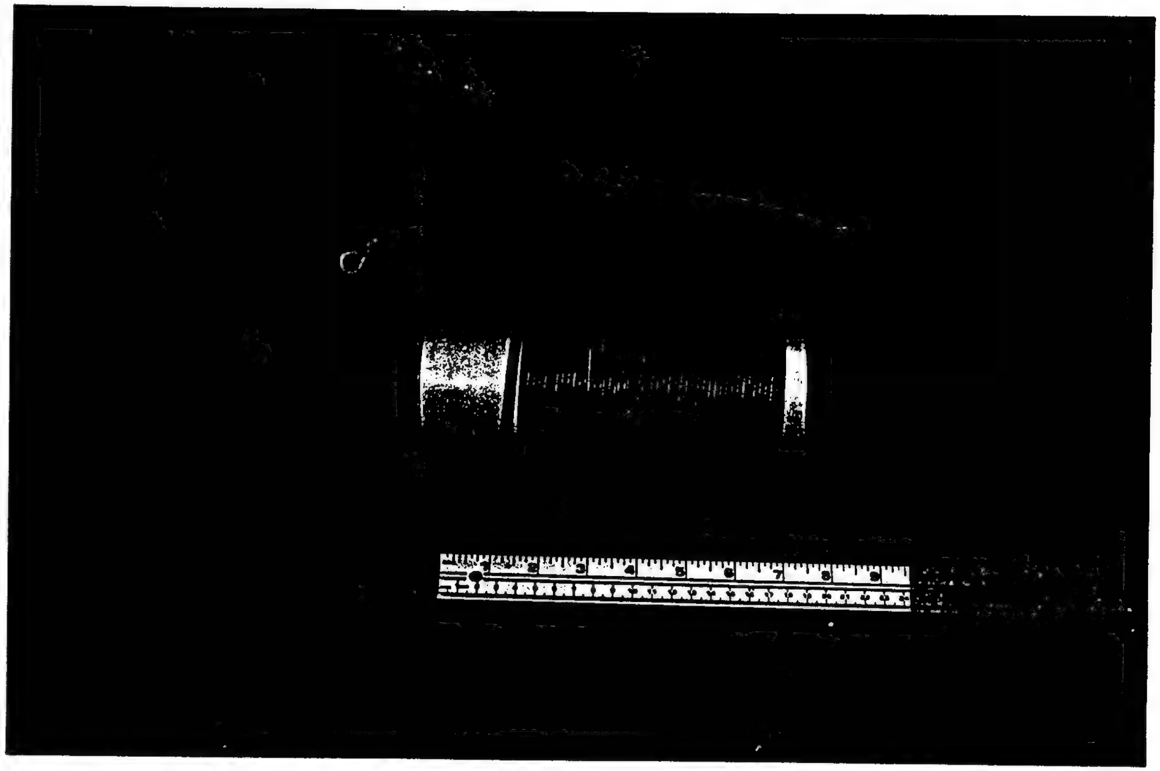


Fig. 4. The new plastic base surface layer plasma generator.

EXPERIMENTAL SET-UP AND OPERATING CHARACTERISTICS OF THE ONE ATMOSPHERE UNIFORM GLOW DISCHARGE PLASMA GENERATORS.

1. Power supply output frequency range: 1 KHz to 20 KHz.

2. Power supply output voltage: up to 8 KV (rms).

3. Plasma operating pressure: 1 atmosphere.

4. Working gas: Air, He, He+Air.

5. Instantaneous power range: Several 10VA to 100 VA(including reactive power).

6. Parallel power connection with the generator base floating.
7. Phosphor: Type: 2461 and 2211; Color: Blue and Green.

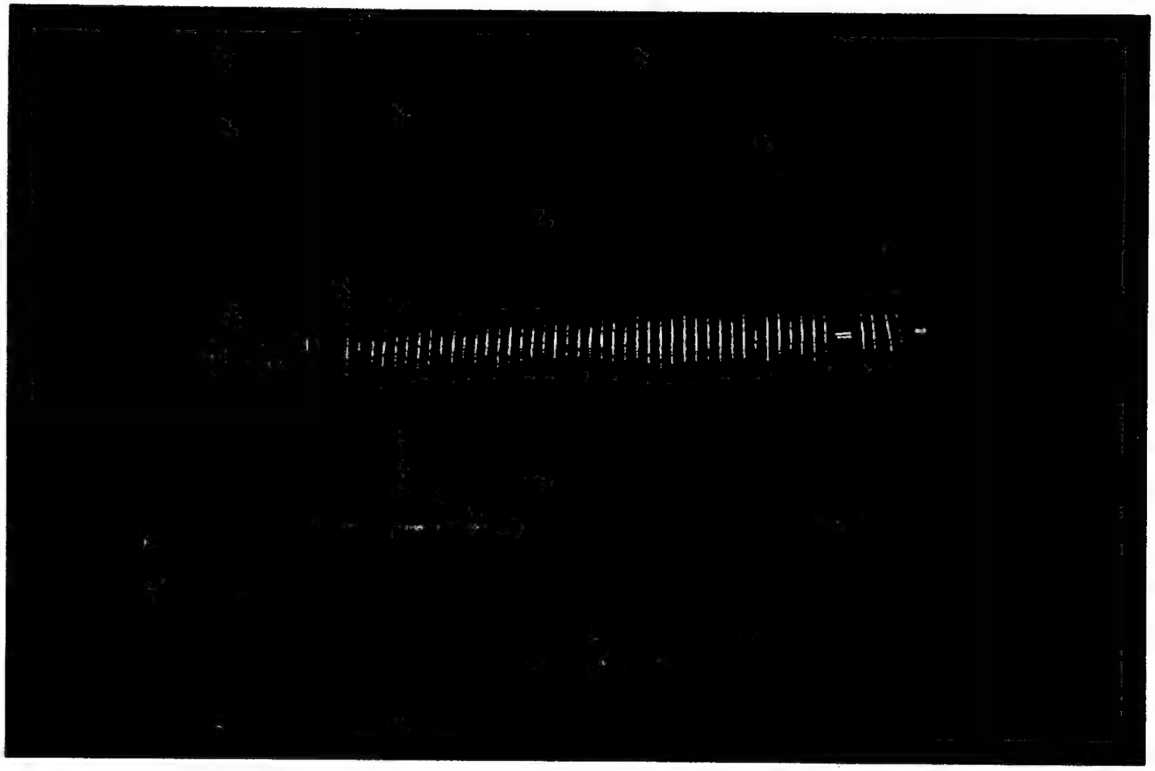


Fig. 5. Photograph of the metal base surface layer plasma generator.

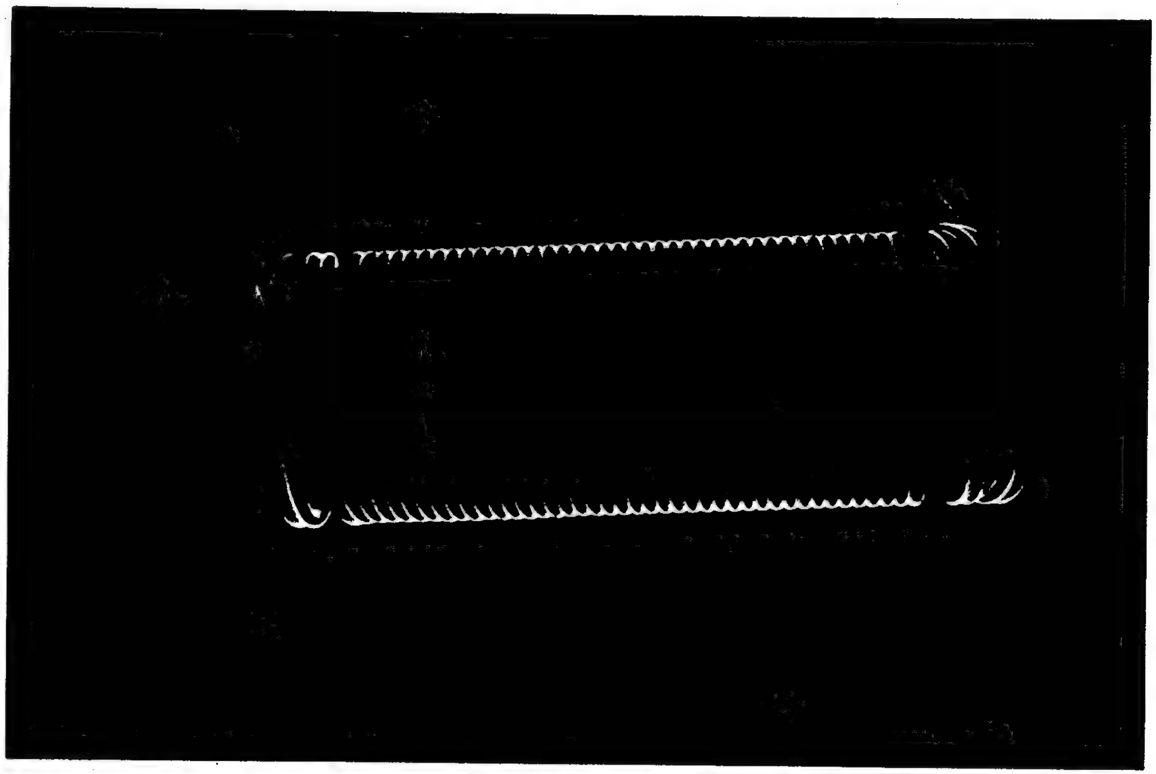


Fig. 6. Photograph of the one atmosphere uniform glow discharge plasma <u>(metal base)</u> using <u>*helium*</u>, taken with an RF frequency f_0=3KHz, and RMS electrode voltage of 2 KV.

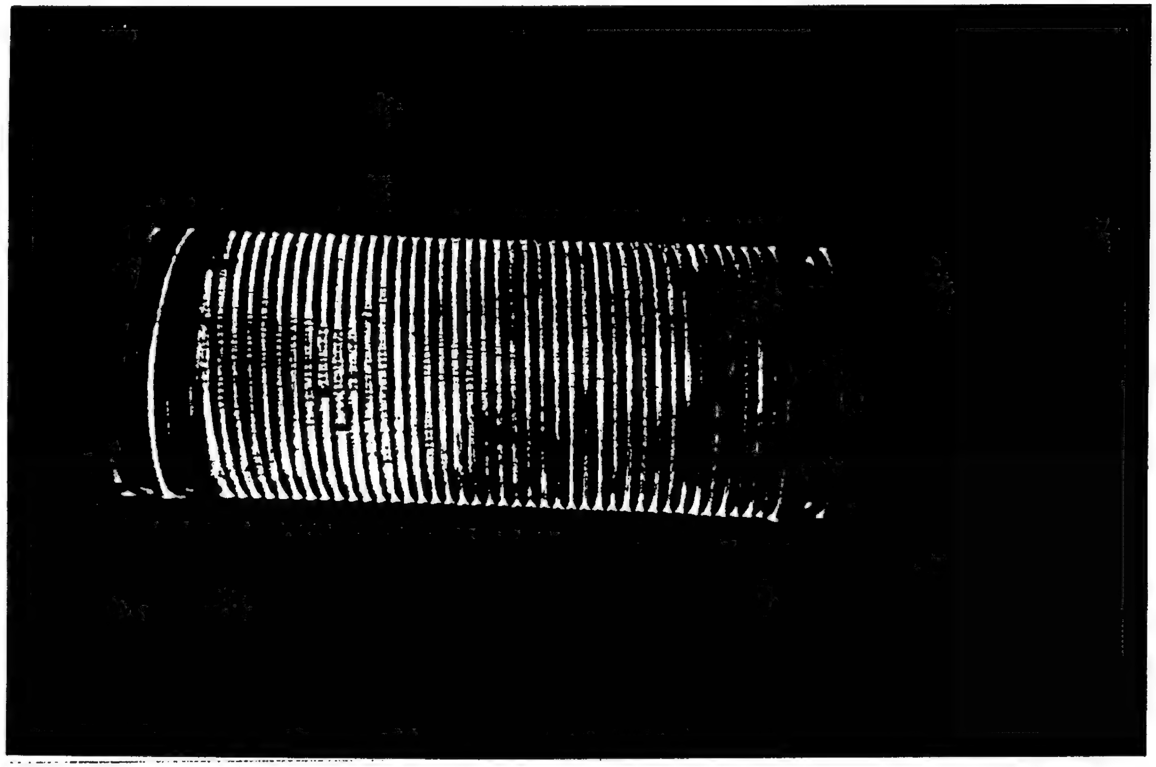


Fig. 7. Photograph of the one atmosphere uniform glow discharge plasma (metal base) using *helium* with phosphor on the surface, taken with an RF frequency f_0=3KHz, and RMS electrode voltage of 2 KV.

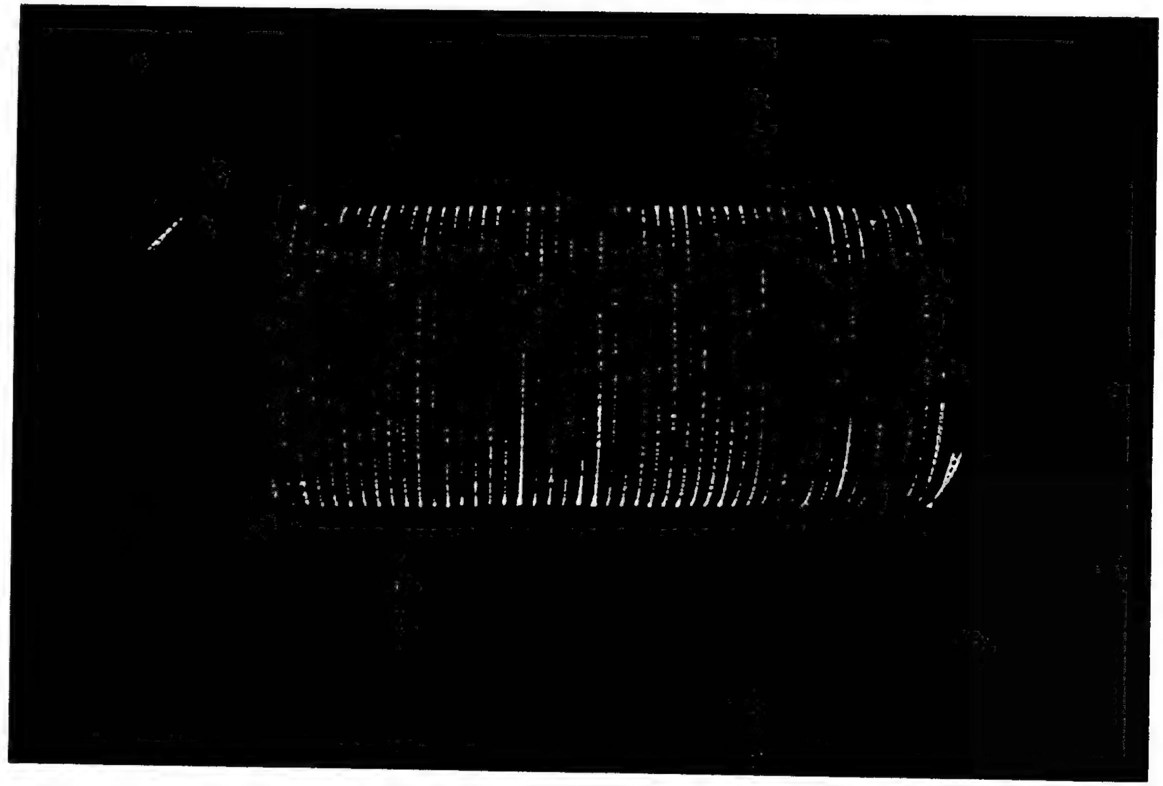


Fig. 8. Photograph of the one atmosphere uniform glow discharge plasma <u>(plastic base)</u> using <u>*air*</u>, taken with an RF frequency f_0=6KHz, and RMS electrode voltage of 2KV.

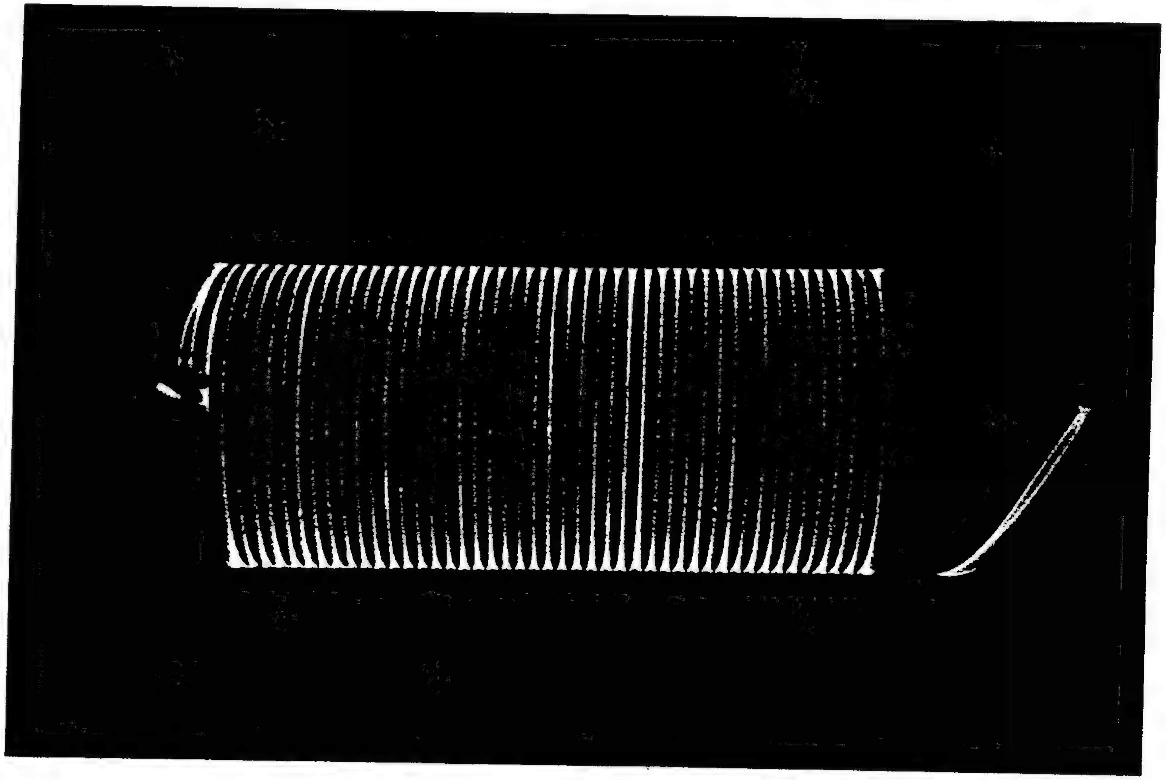


Fig. 9. Photograph of the one atmosphere uniform glow discharge plasma <u>(plastic base)</u> using ***helium***, taken with an RF frequency f_0=6KHz, and RMS electrode voltage of 2KV.

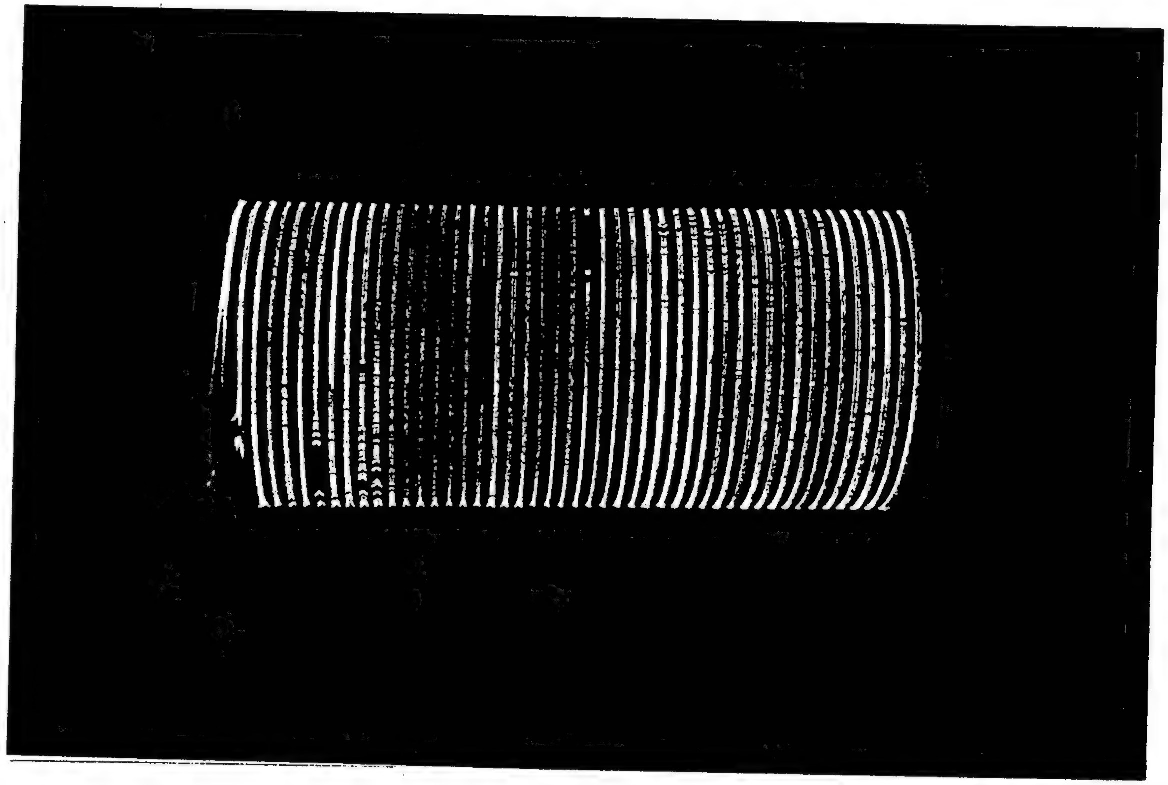


Fig. 10. Photograph of the one atmosphere uniform glow discharge plasma <u>(plastic base)</u> using <u>*air*</u>, with phosphor on the surface, taken with an RF frequency f_0=6KHz, and RMS electrode voltage of 2 KV.

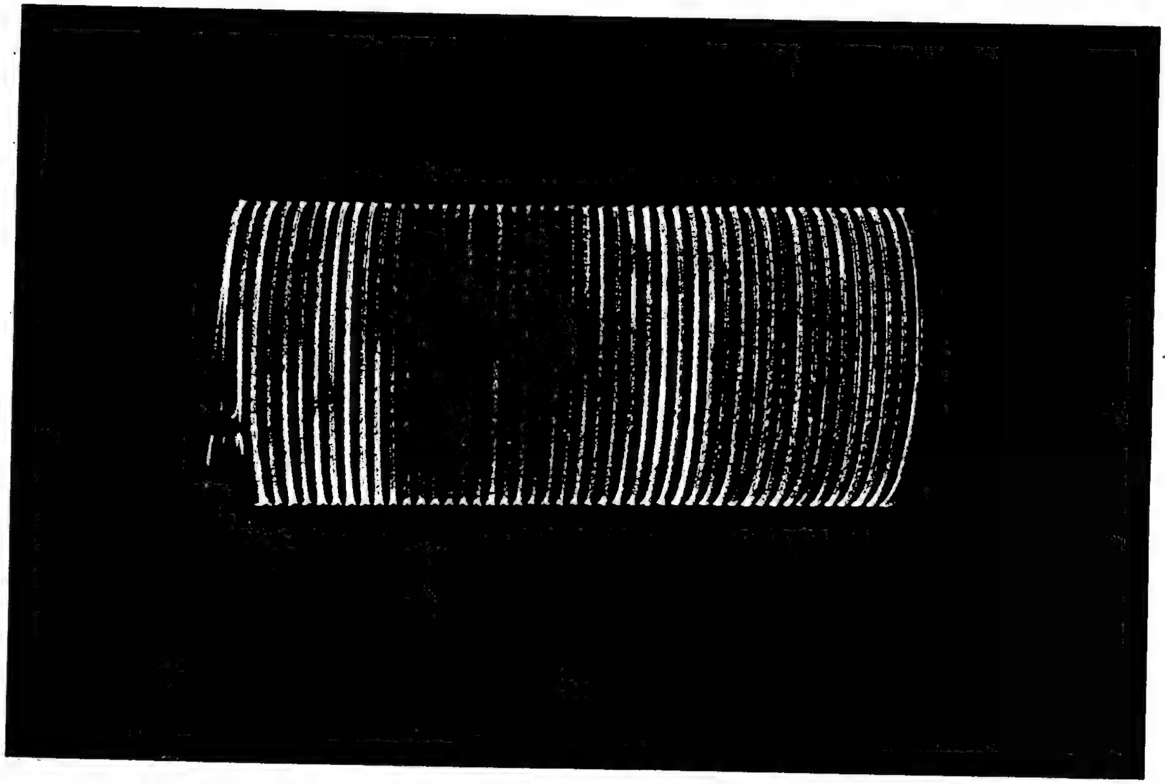


Fig. 11. **Photograph of the one atmosphere uniform glow discharge plasma (plastic base) using *helium*, with phosphor on the surface, taken with an RF frequency f_0=6KHz, and RMS electrode voltage of 2 KV.**

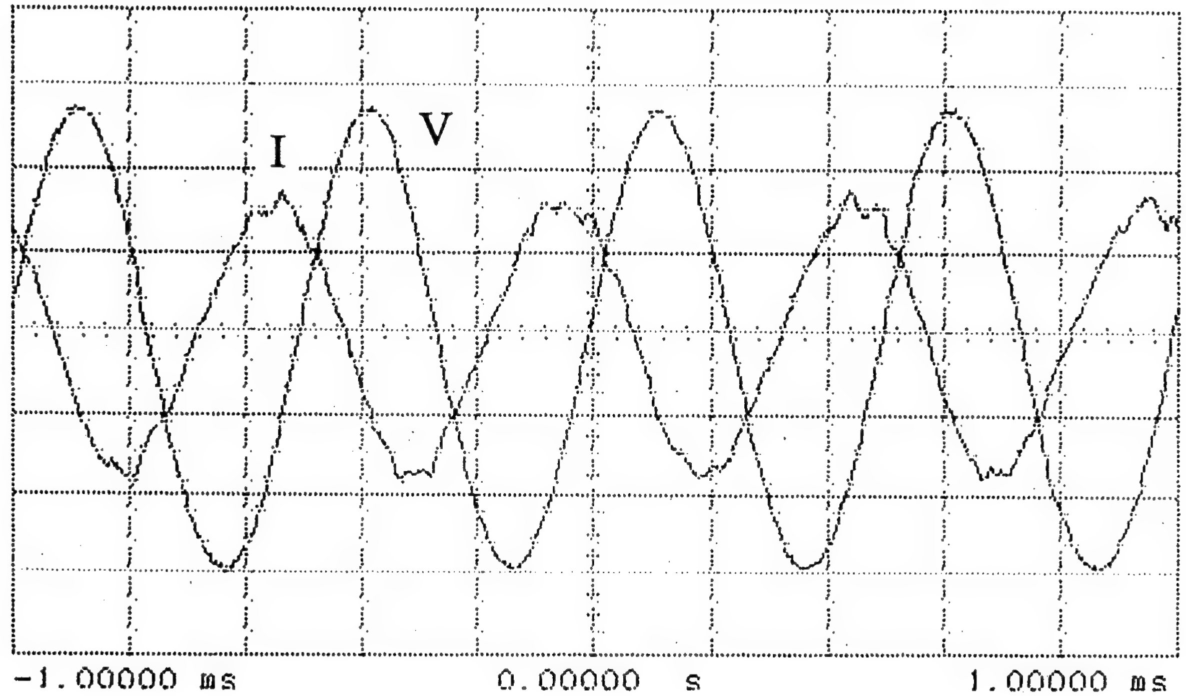


Fig. 12. The waveform of the current and voltage; V_{RMS} =2KV, f_0 =2KHz, *air*; metal base surface layer plasma generator.

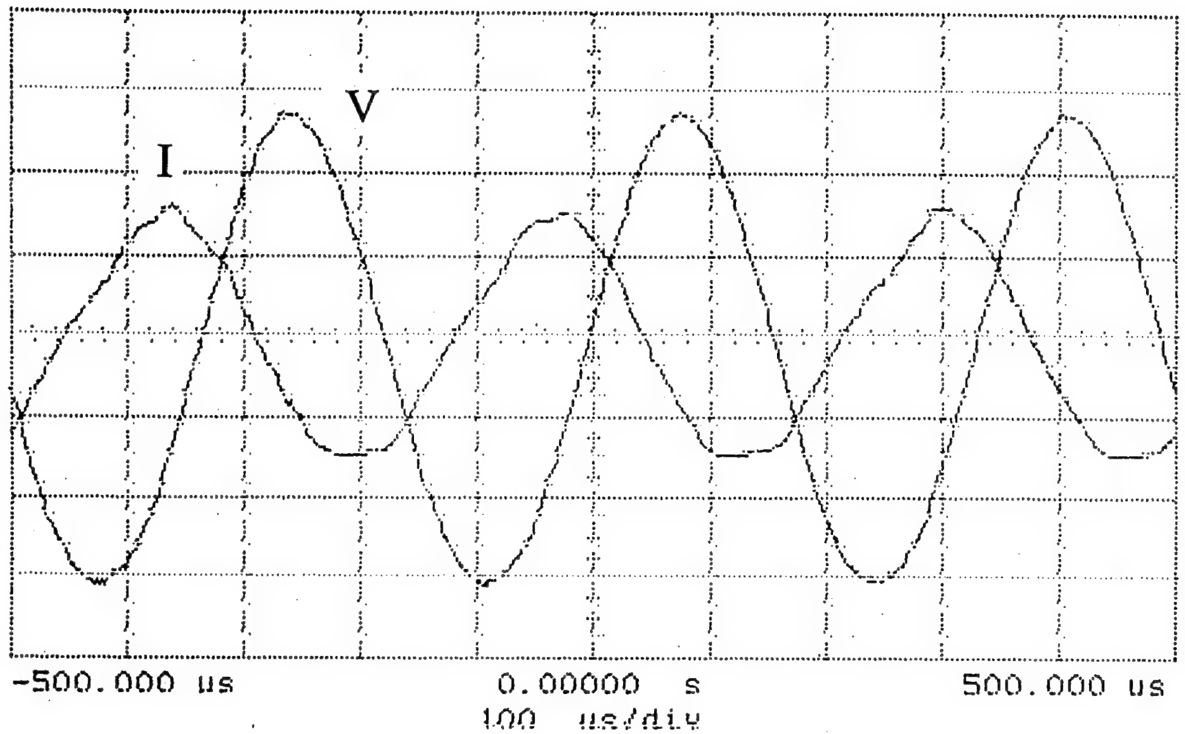


Fig. 13. The waveform of the current and voltage; V_{RMS} =2KV, f_0 =3KHz, *helium*; metal base surface layer plasma generator.

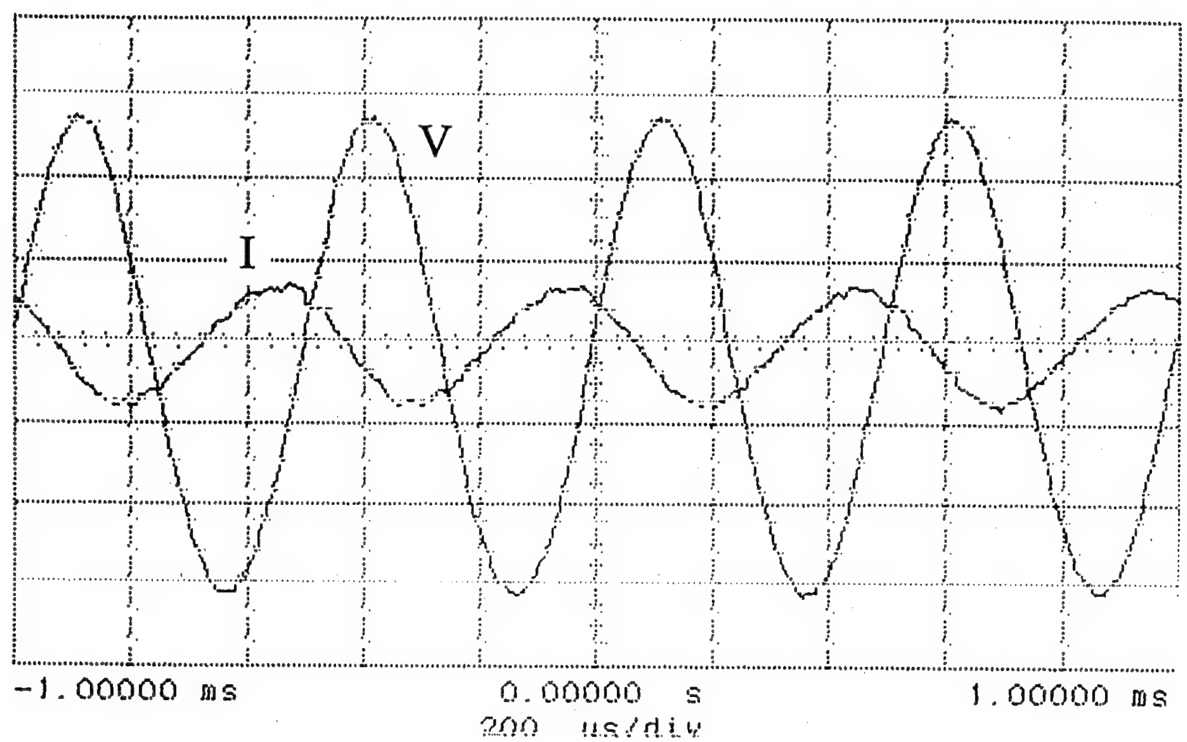


Fig. 14. **The waveform of the current and voltage; V_{RMS} =2KV, f_0 =3KHz, *air* with phosphor on the surface; metal base surface layer plasma generator.**

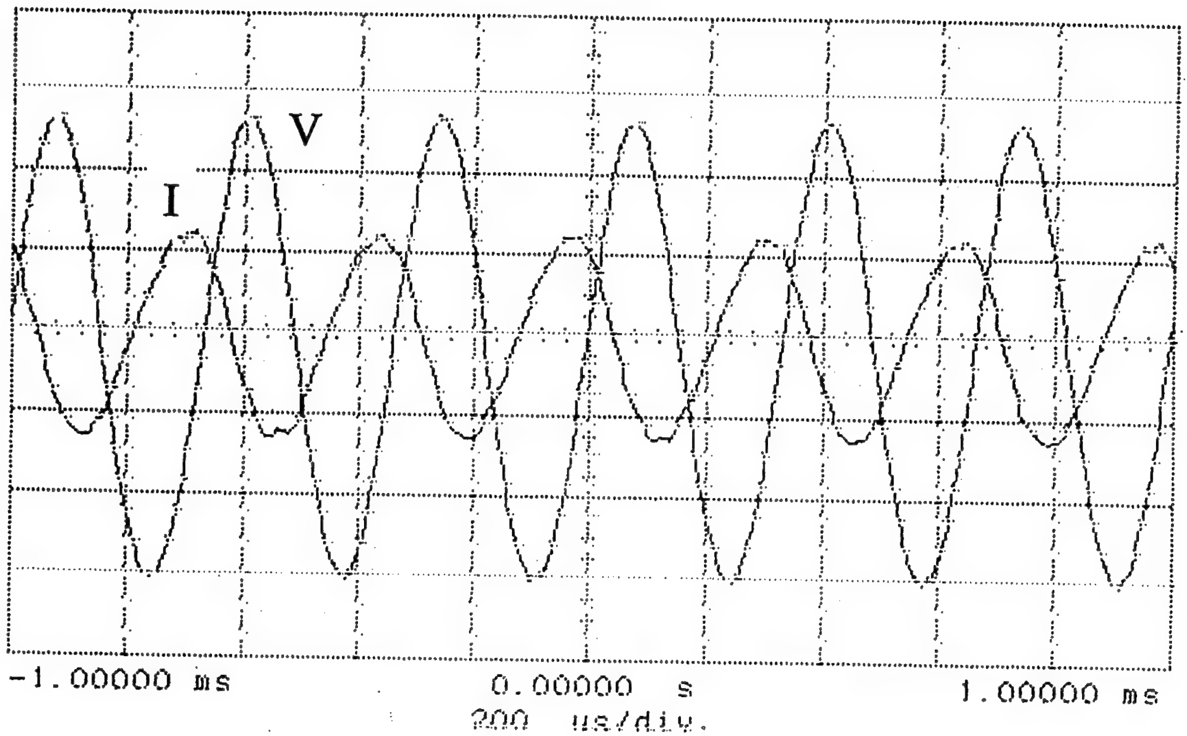


Fig. 15. The waveform of the current and voltage; V_{RMS} =2KV, f_0 =3KHz, *helium* ; phosphor on the surface; metal base surface layer plasma generator.

Acknowledgment

We would like to thank Dr. Gerald L. Rogoff, Engineering manager, GTE Products Corp., and Dr. Barry G. DeBoer of Osram Sylvania Inc., Towanda, PA, for supplying the fluorescent phosphors used in these tests.

FUTURE WORK

1. **Because this discharge operates at high pressure, the electron collision frequency is very high. New diagnostic technology has to be developed.**

2. **Creating a thicker plasma layer on the skin of the surface layer plasma generator is desired.**

3. **Control of this layer of plasma is to be demonstrated.**

4. **Study of physical processes in this plasma is necessary.**

CONCLUSIONS

- Two new surface layer glow discharge plasma generators have been developed.
- This new plasma generator can create a thin surface layer of uniform plasma.
- We have created a layer of uniform, steady-state glow discharge plasma on the surface metal and plastic in air and helium.
- The plasma excites the fluorescence on a phosphor below the plasma layer.
- These surface glow discharge plasma generators could find industrial and other applications.

- This surface glow discharge plasma generator is a capacitive plasma generator.
- The surface layer of plasma on the simulated aircraft fuselage survived exposure to a high-velocity air jet driven by a 2.5 atmosphere pressure differential.
- The one atmosphere fluorescent lamp is capable of operating at one atmosphere without using mercury vapor to excite the phosphors
- The kilohertz RF frequencies required should be below the limit of regulatory interest.

Paper 6EP10

BOUNDARY LAYER CONTROL BY A ONE ATMOSPHRE UNIFORM GLOW DISCHARGE PLASMA LAYER*

by

J. Reece Roth
UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
The University of Tennessee
Knoxville, Tennessee, 37996-2100

Presented at the 22nd IEEE International Conference on Plasma Science Madison, Wisconsin, June 5-8, 1995

*Supported in part by the Air Force Office of Scientific Research Under Contract AFOSR F49620-94-10249

ABSTRACT

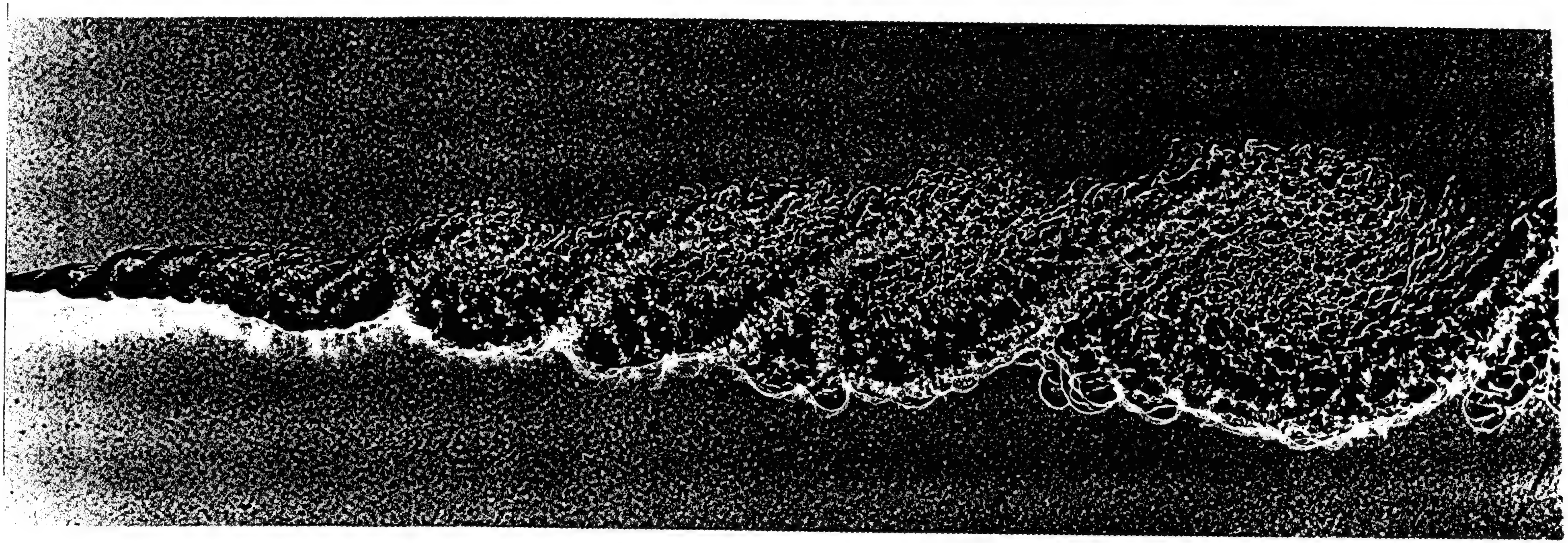
At the University of Tennessee's Plasma Science Laboratory, we have recently developed, with AFOSR support, a new type of uniform glow discharge plasma which is capable of operating at one atmosphere in air and other gases.[1] This plasma is neither a corona discharge nor a filamentary (ozonizer) discharge, the more familiar plasma discharges also capable of operating at one atmosphere. The physical processes which make this discharge possible, based on an RF ion trapping mechanism, will be described theoretically, and the RF frequency, electric field, and electrode separation required to maintain this discharge will be derived from first principles. Characteristic operating and plasma parameters in air at one atmosphere are: RF frequency, 1-6 kHz, RMS electric field, 9 kV/cm; maximum RMS voltage, 4 kV; plasma number density, 10^{10} electrons/cm^3; and input power density, 10-200 milliwatts/cm^3. The maximum volume of uniform plasma generated to date has been 2.8 liters between parallel plates.

More recently, the parallel plate geometry described above has been geometrically transformed and made to operate on a planar surface, producing a steady-state plasma layer up to several millimeters thick. The electric field in this surface plasma layer can provide a body force per unit area of up to several thousand pascals. Some speculative applications to boundary layer control, turbulence suppression, drag reduction and noise reduction will be put forward.

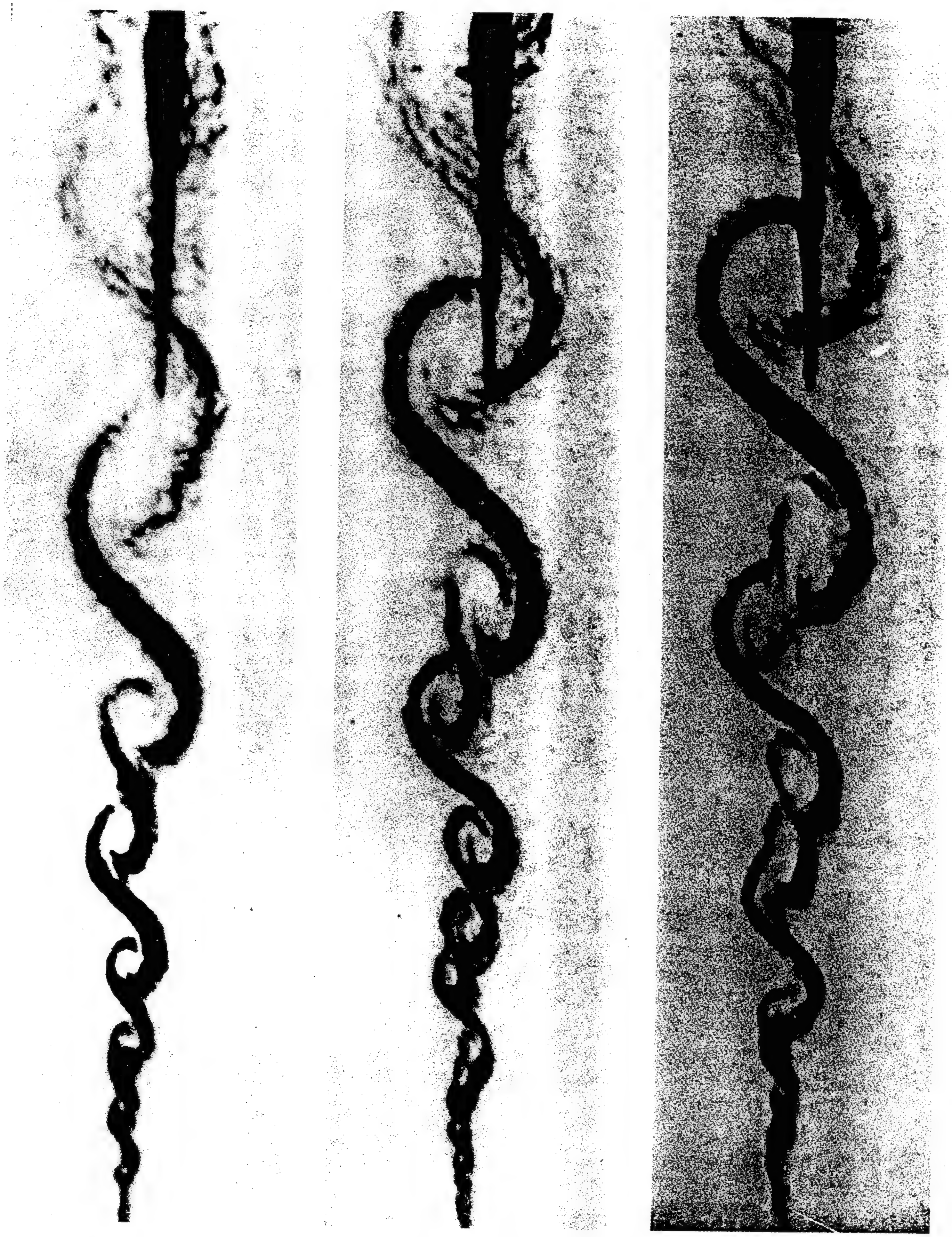
*Supported in part by AFOSR contract F49620-94-10249 (Roth). Aerodynamic data were kindly furnished by S. P. Wilkinson, NASA LaRC.

1. J. R. Roth, C. Liu, and M. Laroussi: "Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure". Proc. IEEE International Conf. on Plasma Science, ISBN0-7803-0716-X (1992) pp. 170-171.

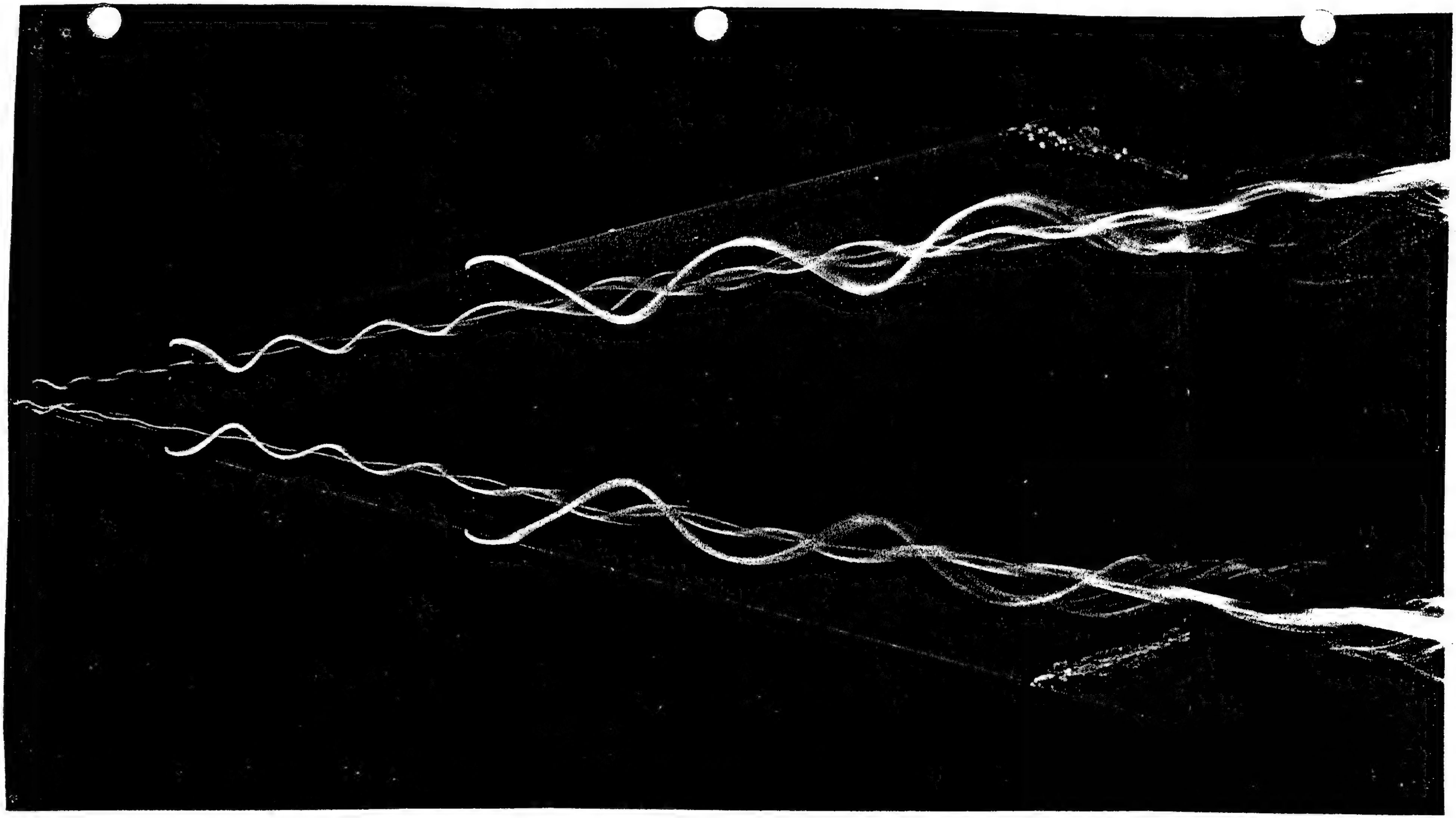
The Following Photos Were Taken from M. Van Dyke, An Album of Fluid Motion, the Parabolic Press, Stanford, CA (1982) ISBN 0-915760-02-9 (Pbk). They illustrate the growth of turbulence and vortices, both of which contribute to skin drag, from very small initial disturbances.



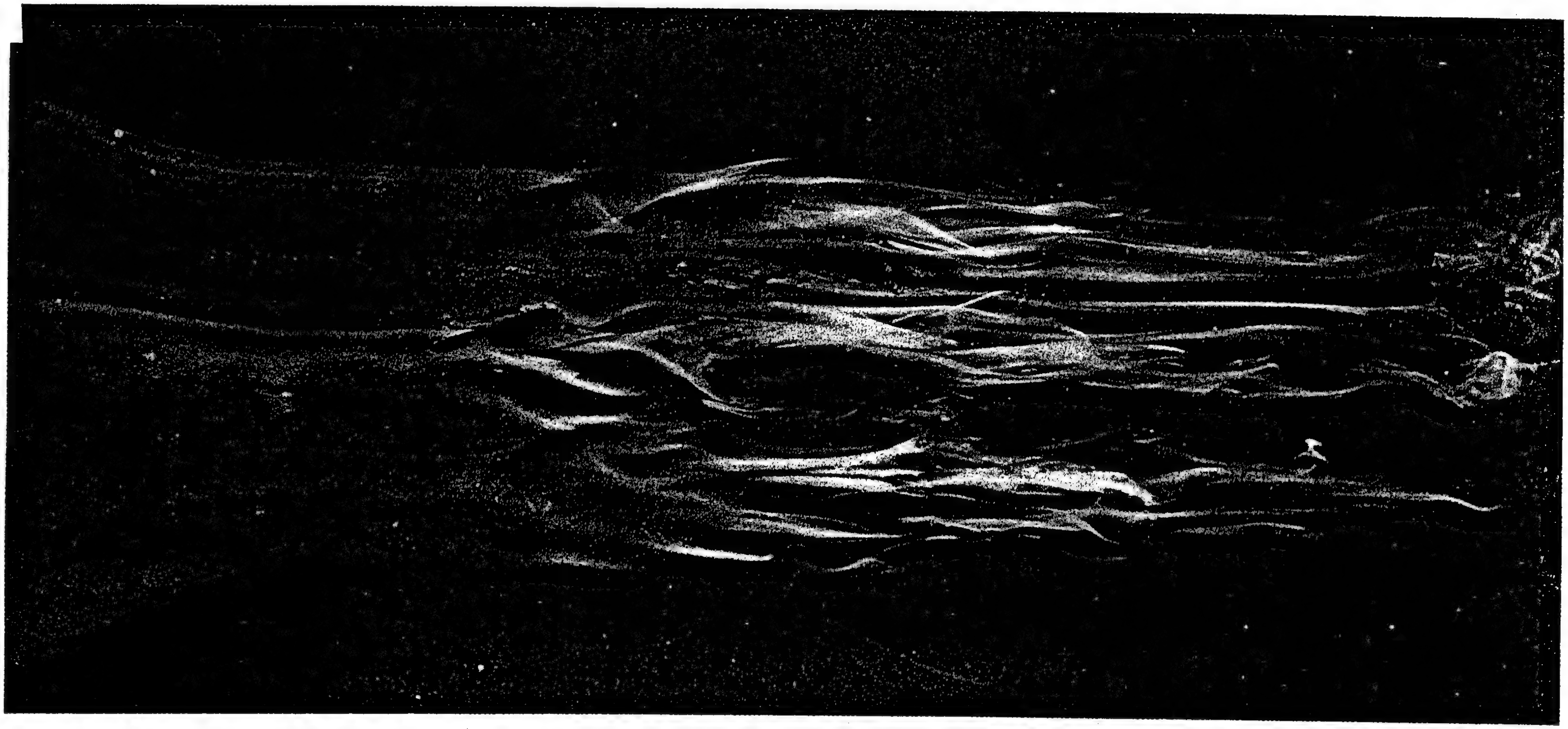
177. Coherent structure at higher Reynolds number. This flow is as above but at twice the pressure. Doubling the Reynolds number has produced more small-scale structure without significantly altering the large-scale structure. *M. R. Rebollo, Ph.D. thesis, Calif. Inst. of Tech., 1976; Brown & Roshko 1974*



158. Turbulent boundary layer on a wall. A fog of tiny oil droplets is introduced into the laminar boundary layer on the test-section floor of a wind tunnel, and the layer then tripped to become turbulent. A vertical sheet of light shows the flow pattern 5.8 m downstream, where the Reynolds number based on momentum thickness is about 4000. *Falco 1977*



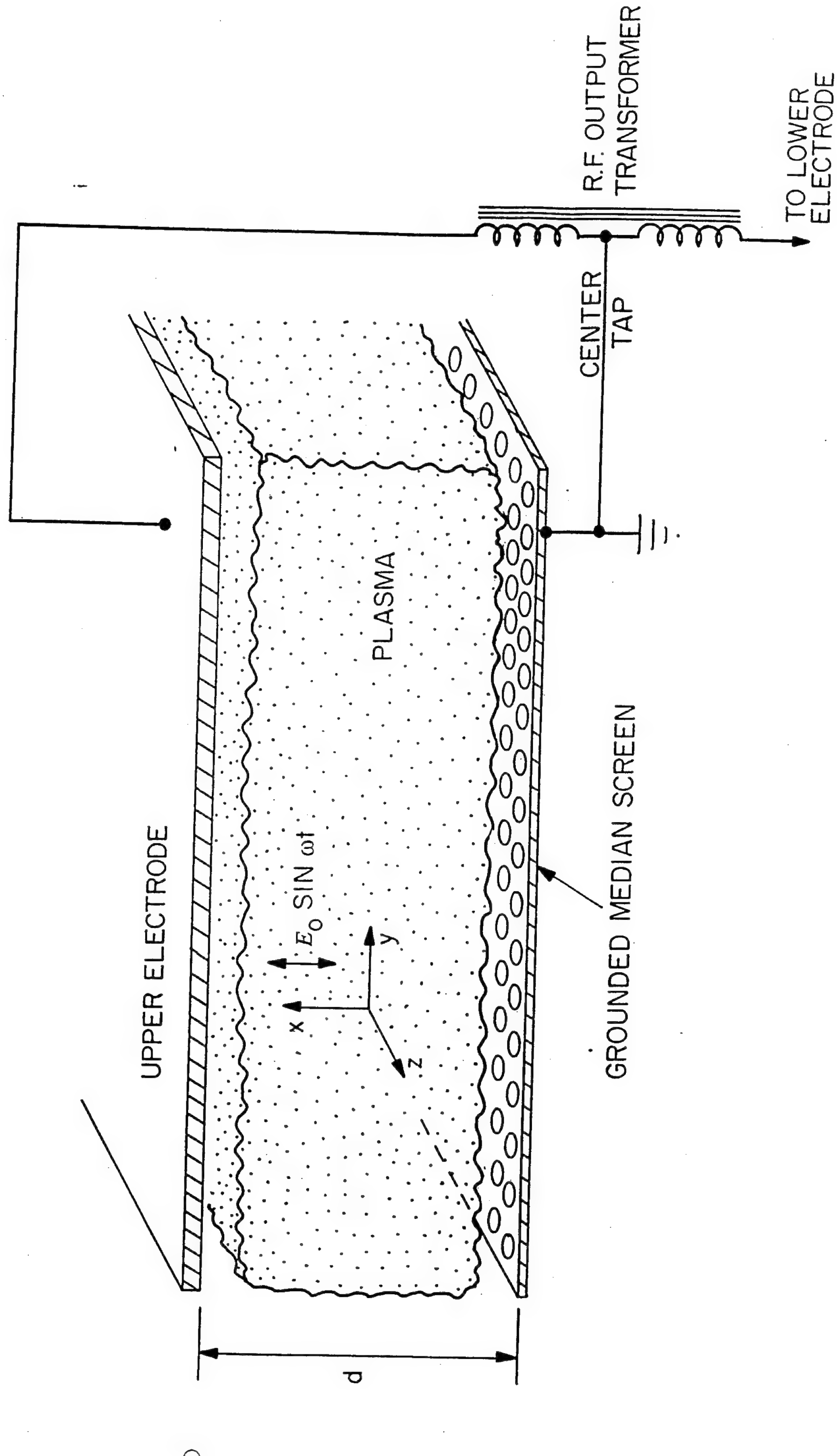
90. Vortices above an inclined triangular wing. Lines of colored fluid in water show the symmetrical pair of vortices behind a thin wing of 15° semi-vertex angle at 20° angle of attack. The Reynolds number is 20,000 based on chord. Although the Mach number is very low, the flow field is practically conical over most of the wing, quantities being constant along rays from the apex. *ONERA photograph, Werlé 1963*



105. Natural transition on a slightly inclined plate. At the same Reynolds number of 100,000 but 1° angle of attack, transition to turbulence occurs on the plate. *ONERA photograph, Werlé 1980*

The <u>O</u>ne <u>A</u>tmosphere <u>U</u>niform <u>G</u>low <u>D</u>ischarge <u>P</u>lasma OAUGDP:

- **Operates on displacement currents - no exposed electrodes necessary.**
- **Will generate a thin plasma layer in a planar configuration.**
- **Uniform, high density, large volume plasmas possible**
- **High power densities possible**
- **Electrons non-thermal over a large volume (hence the "glow")**



R.F. OUTPUT TRANSFORMER
TO LOWER ELECTRODE
CENTER TAP
PLASMA
UPPER ELECTRODE
E_0 SIN ωt
x
y
z
GROUNDED MEDIAN SCREEN
d

In the parallel plate geometry, the vertical RF electric field is

$$E = (E_o \sin \omega t, 0, 0). \quad (1$$

The Lorentzian equation of motion is

$$F = m\ a = -\ m\ \nu_c\ V - eE, \quad (2$$

The x-component normal to the plates is

$$m \frac{d^2x}{dt^2} + m\,\nu_c \frac{dx}{dt} = eE_o \sin\omega t, \quad (3$$

The general solution to Eq. 3 is

$$x = C_1 \sin\omega t + C_2 \cos\omega t. \quad (4$$

where the constants C_1 and C_2 are given by

$$C_1 = - \frac{eE_o}{m} \frac{1}{\left(\omega^2 + \nu_c^2\right)}, \qquad (5$$

and

$$C_2 = - \frac{\nu_c \, eE_o}{\omega \, m} \frac{1}{\left(\omega^2 + \nu_c^2\right)}. \qquad (6$$

For helium, the ion and electron collision frequencies at one atmosphere are approximately

$$\nu_{ci} \approx 6.8 \times 10^9 \text{ ion collisions/sec.} \qquad (7a$$

$$\nu_{ce} \approx 1.8 \times 10^{12} \text{ electron collisions/sec.} \qquad (7b$$

for the OAUGDP, $\nu_c >> \omega$, therefore

$$C_2 \approx - \frac{eE_o}{m \, \omega \, \nu_c} >> C_1. \qquad (8$$

Substituting Eq. 8 into Eq. 4,

$$x(t) \approx - \frac{eE_o}{m \, \omega \, \nu_c} \cos \omega t. \qquad (9$$

The RMS displacement during a half-cycle is

$$x_{rms} = \frac{2}{\pi} \frac{eE_o}{m \, \omega \, \nu_c} \text{ meters.} \qquad (10$$

If ν_o is the driving frequency in Hz,

$$\omega = 2\pi\nu_o. \qquad (11$$

The maximum electric field between the parallel plates can be written

$$E_o = \frac{V_o}{d} = \frac{\pi V_{rms}}{2d}. \qquad (12$$

For ion trapping between the plates,

$$x_{rms} \leq \frac{d}{2} . \qquad (13$$

Substituting Eqs. 11 to 13 into Eq. 10 yields

$$\frac{d}{2} \approx \frac{e\,V_{rms}}{2\pi\, m\, \nu_o\, \nu_c\, d} . \qquad (14$$

The critical frequency ν_o above which charge buildup should occur is

$$\nu_o \approx \frac{e\,V_{rms}}{\pi m\, \nu_c\, d^2} \text{ Hz.} \qquad (15$$

Note that

$$m_e\, \nu_{ce} < M\, \nu_{ci}$$

so that

$$\nu_{oe} > \nu_{oi}$$

Typically, ν_{oi} is of the order of kHz.

PLASMA POWER DENSITY

The work done on a single charge between the plates is

$$W = F.dx = eE(t)dx \text{ (J).} \qquad (16$$

The power delivered to this charge is

$$p = \frac{dW}{dt} = eE(t)\frac{dx}{dt} = eE(t)\dot{x} \qquad \text{(W / electron).} \qquad (17$$

Taking the derivative of Eq. 4,

$$\dot{x} = C_1\,\omega\cos\omega t - C_2\,\omega\sin\omega t. \qquad (18$$

Substituting Eqs. 1 and 18 into Eq. 17,

$$p = e\,E_o \omega C_1 \sin \omega t \cos \omega t - e\,E_o\, \omega C_2 \sin^2 \omega t \qquad (19$$

The average power per unit volume is found by multiplying Eq. 19 by n_e, and integrating over a cycle of operation. The first term of Eq. 19 averages to zero, leaving

$$\overline{P} = n_e\, \overline{p} = \frac{n_e e\, E_o\, \omega C_2}{2\pi} \int_0^{2\pi} \sin^2 \omega t\, d(\omega t)$$

$$= \frac{n_e e\, E_o\, \omega C_2}{2} \; (W/m^3). \qquad (20$$

Substituting Eq. 6 for C_2, Eq. 20 becomes

$$\overline{P} = - \frac{n_e\, e\, E_o\, \omega}{2} \times \frac{\nu_c e\, E_o}{\omega m\left(\omega^2 + \nu_c^2\right)} = - \frac{e^2 E_o^2 \nu_c n_e}{2m\left(\omega^2 + \nu_c^2\right)} \qquad (21$$

Since $\nu_c >> \omega$, Eq. 21 can be approximated as

$$\overline{P} \approx - \frac{n_e e^2 E_o^2}{2m \nu_c}. \qquad (22$$

Using Eq. 12 to write E_o in terms of V_{rms},

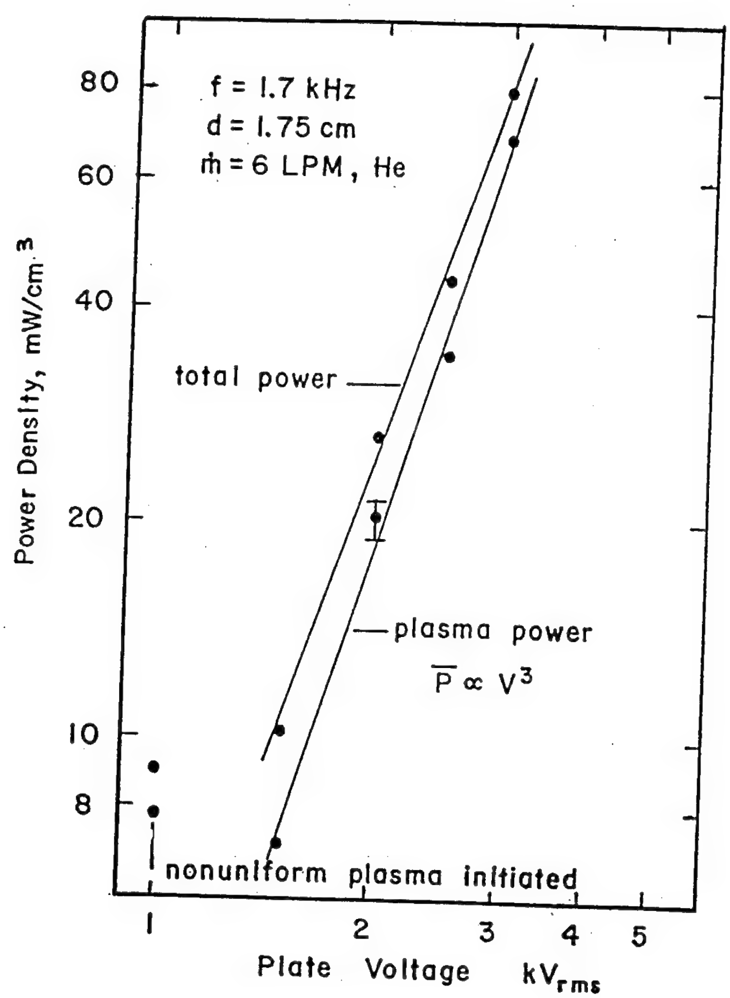
$$\overline{P} = - \frac{n_e e^2}{2m \nu_c} \frac{\pi^2 V_{rms}^2}{4 d^2} = - \frac{\pi^2 e^2 V_{rms}^2}{8m \nu_c d^2} \quad (W/m^3). \qquad (23$$

Experimental data appears to show a dependence

$$\overline{P} \sim V_{rms}^3$$

The relative power delivered to the electron and ion populations can be found by ratioing Eq. 23,

$$\frac{\overline{P}_i}{\overline{P}_e} = \frac{m_e \nu_{ce}}{M \nu_{ci}} \qquad (24$$



Power density scaling as a function of plate voltage.

Where M is the ion mass. For helium,

$$\frac{\overline{P}_i}{\overline{P}_e} = \frac{1.8 \times 10^2}{4 \times 1837 \times 6.8 \times 10^9} = .036. \qquad (25$$

In helium, most of the power is delivered to the electron population.

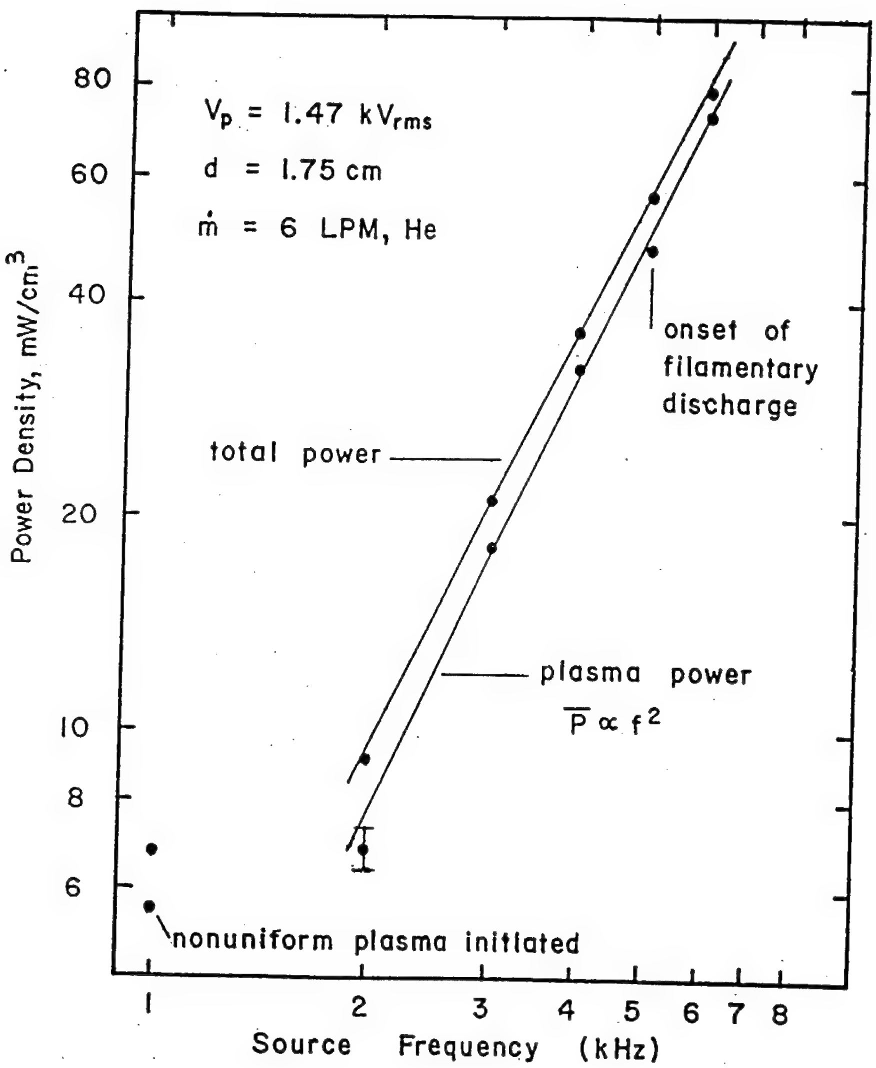
Solving Eq. 15 for V_{rms},

$$V_{rms} \approx \frac{\pi \nu_o m \nu_c d^2}{e} \text{ volts} \qquad (26$$

Substituting this into Eq. 23, the power density is

$$\overline{P} = \frac{\pi^4}{8} m \nu_c d^2 \nu_o^2 \qquad \text{watts/m}^3 \qquad (27$$

This functional dependence of $\overline{P}$ on ν_o^2 has been experimentally observed.



Power density scaling as a function of source frequency.

TABLE I

OPERATING CHARACTERISTICS OF THE ONE ATMOSPHERE GLOW DISCHARGE PLASMA REACTOR

working gas = H_e, CO_2, CO_2 + 3-10% O_2, Air.

frequency = 1 KHz to 100 KHz

voltage = 1.5 - 9.5 kV_{rms} plate to plate

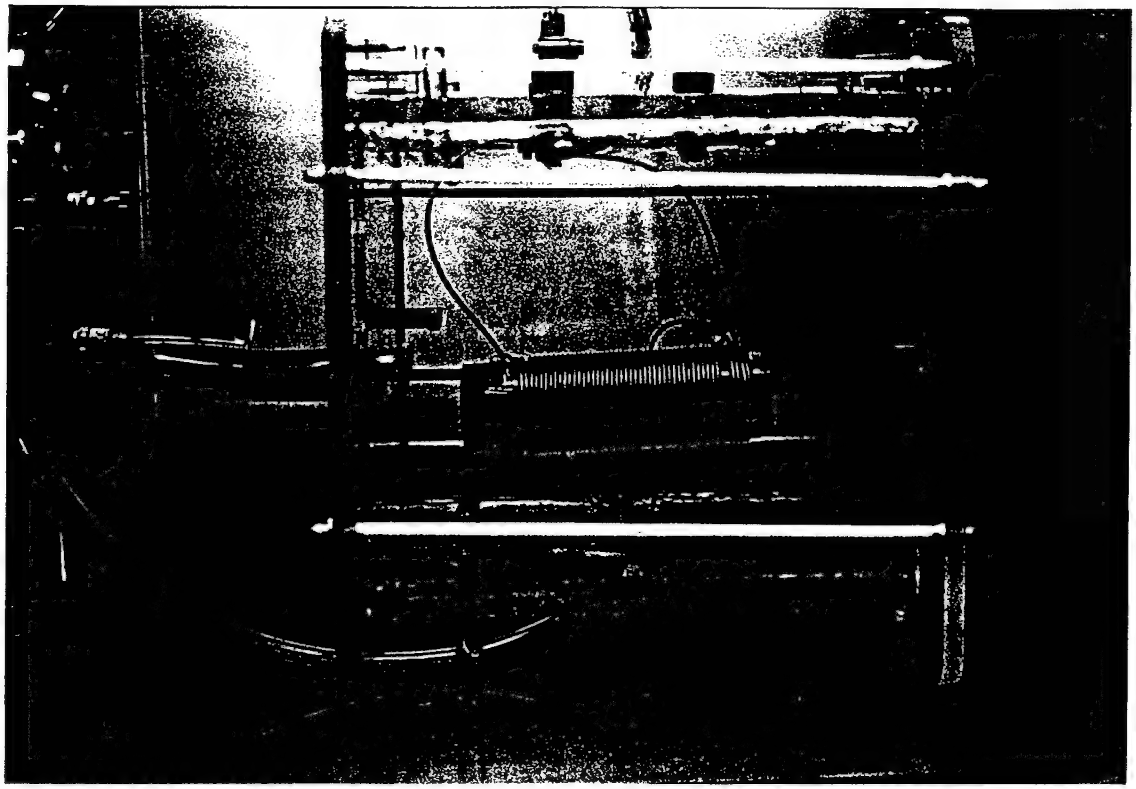
electrode gap d = 0.25 - 2.5cm

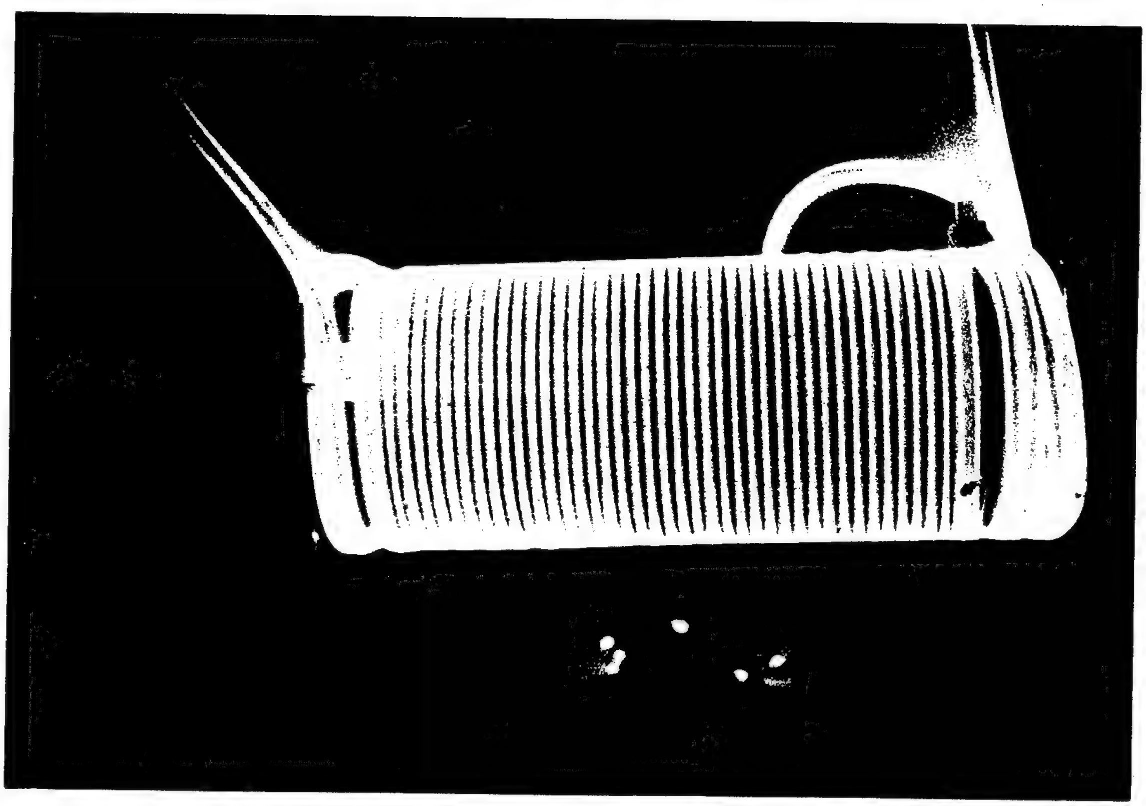
pressure = 760 +15, -5 Torr

RMS power = 10 watts to 150 watts

Power density = 4 - 120 mW/cm^3

plasma volume = 0.053 - 0.53 liters

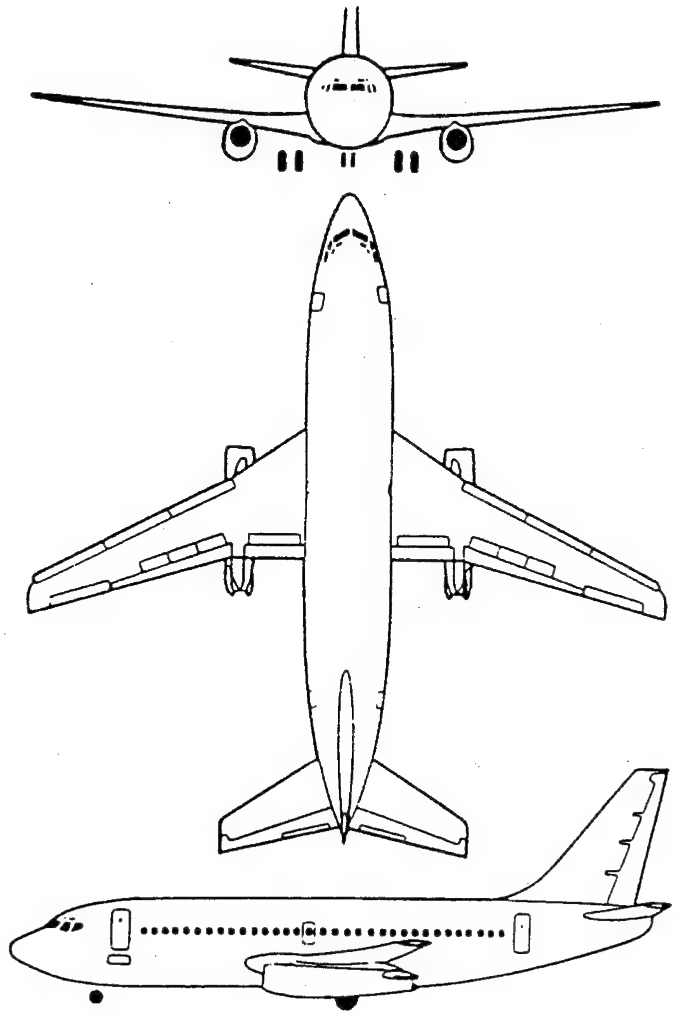




SIMULATED AIRCRAFT FUSELAGE, 5 CM DIA, IN HELIUM

For more information on the One Atmosphere Uniform Glow Discharge Plasma (OAUGDP), see J. R. Roth, "Industrial Plasma Engineering: Volume I-Principles", Institute of Physics Press, Bristol, UK (1995) ISBN 0-7503-0318-2 (paperback) $42.00 Chapter 12, Section 12.5.2, pp 453-461.

GEOMETRICAL CHARACTERISTICS OF THE BOEING 737-200 AIRCRAFT



Boeing 737-200

Wing Span: 93 ft

Length: 100 ft

Max. Speed at 100,000 lb and 33,000 ft = 462 knots

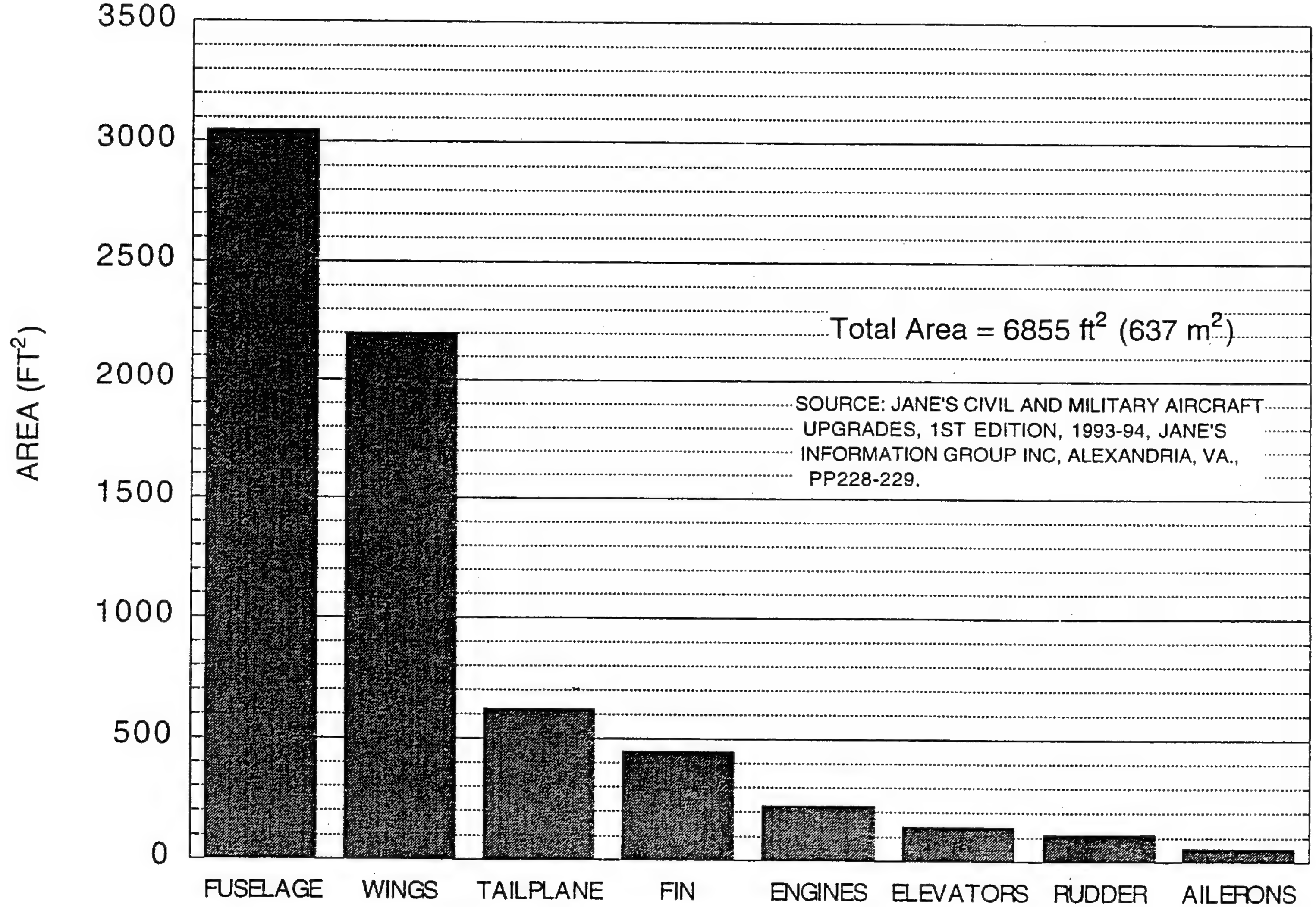
Engines: PW JT8D-17A rated at 16,000 lb st each

Approx. L/D at Cruise: 18

DATA COURTESY OF S. P. WILKINSON, NASA-LANGLEY RESEARCH CENTER

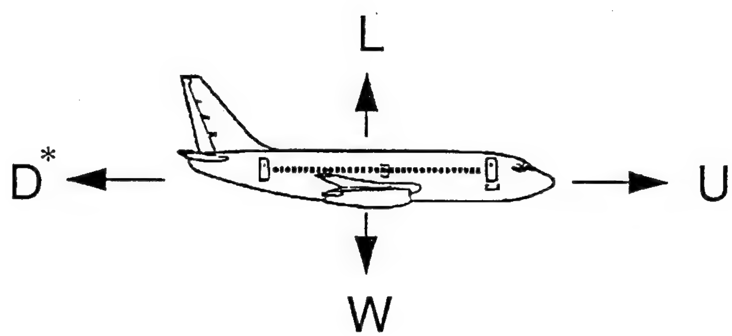
APPROXIMATE SURFACE AREAS OF BOEING 737-200

(External Wetted Area, Both Sides Where Applicable)



DATA COURTESY OF S. P. WILKINSON, NASA-LANGLEY RESEARCH CENTER

Power Requirement Estimate for Boeing 737-200 at Cruise



Power = Drag x Velocity

Drag = Weight / (L/D)

P = W x U / (L/D)

for:

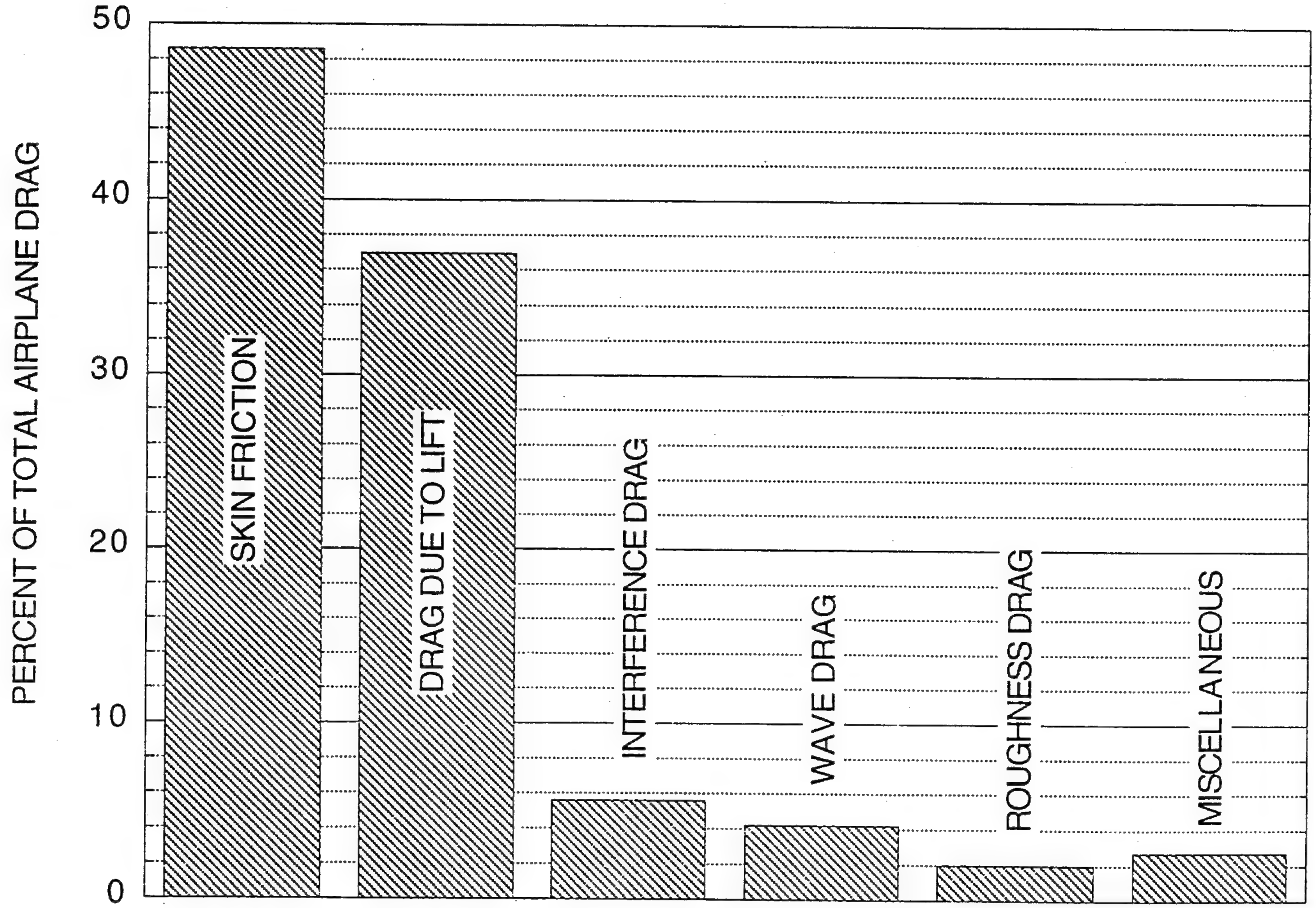
W = 100,000 lbm
U = 462 knots
L/D = 18

P = 7878 HP = 5877 KW

*D includes all drag components including skin friction, drag due to lift, etc

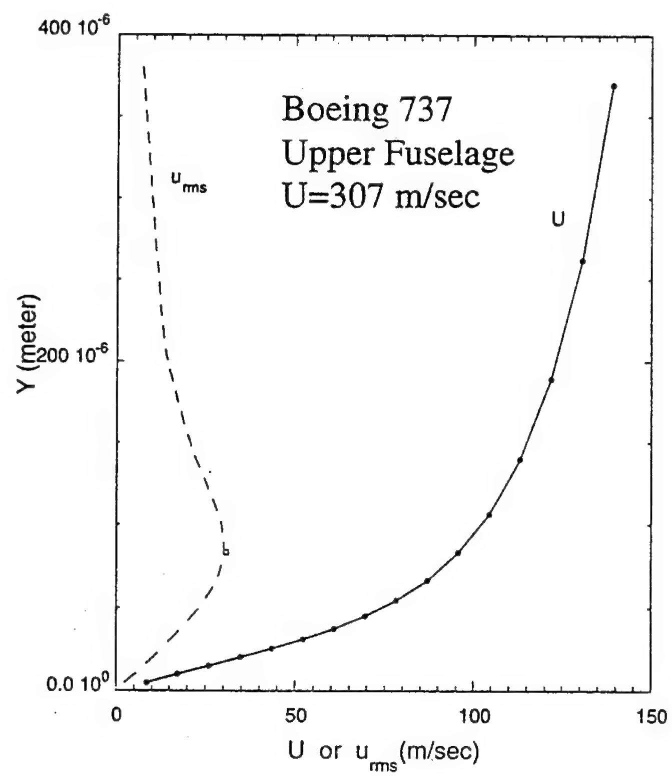
DATA COURTESY OF S. P. WILKINSON, NASA-LANGLEY RESEARCH CENTER

DRAG MAKEUP OF TYPICAL SUBSONIC TRANSPORT AT CRUISE

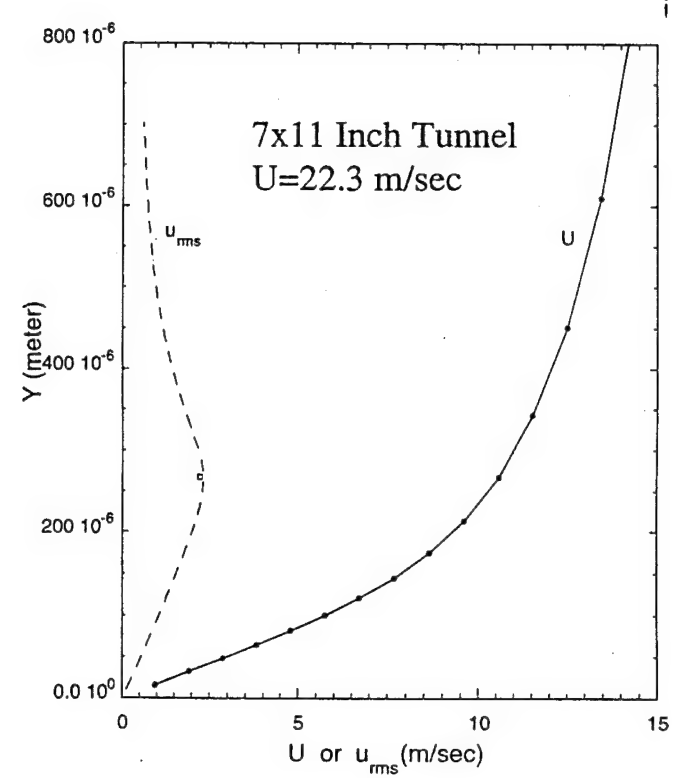


DATA COURTESY OF S. P. WILKINSON, NASA-LANGLEY RESEARCH CENTER

FLIGHT PROFILE



LOW SPEED WIND TUNNEL PROFILE



VELOCITY PROFILES FOR BOEING 737 IN FLIGHT AND LOW SPEED WIND TUNNEL TESTS: SOLID CURVE-VELOCITY; DOTTED CURVE-TURBULENT VELOCITY FLUCTUATIONS

DATA COURTESY OF S. P. WILKINSON, NASA-LANGLEY RESEARCH CENTER

BOUNDARY LAYER CONTROL ISSUES

1. Might the passive plasma layer increase the effective boundary layer thickness and worsen the drag?

2. Will the presence of a passive plasma layer "stiffen" the boundary layer, suppress vortices/turbulence, and reduce drag?

3. Is active manipulation of the plasma with the RF electric field necessary to reduce noise, turbulence, vortices, and drag?

4. If active manipulation is required, should it take the form of "peristaltic" surface waves, or two-dimensional "adaptive fluid dynamics"?

ELECTROSTATIC BODY FORCE/PRESSURE ON BOUNDARY LAYER

If the plasma layer is t = 2mm thick, and has n_e electrons/m^3, the body force on the electrons is

$$F' = n_e e E_{rms} \quad \text{newtons/m}^3$$

The electrostatic pressure is

$$p_E \approx n_e t\, e E_{rms} = n_e t e \frac{V_{rms}}{d} \quad \text{pascals}$$

In a flat plate geometry, $t \approx$ 2mm, $d \approx$ 2.5mm, $V_{rms} \approx 10^4$ volts, and $n_e \approx 10^{16}/\text{m}^3$. For these conditions,

$$p_e \approx 13 \text{ Pascals}, \approx 10^{-4} \text{ atm.}$$

It should, if necessary, be possible to increase t to 1 cm, n_e by 20 times, to yield $p_e \approx$ 1000 pascals, 10^{-2} atm.

<u>Plasma Stability in an Airflow</u>

Under what conditions will the trapped-ion plasma be "blown away" by the airflow? The worst case is if the ions cannot replenish themselves during a half-period of oscillation, and are convected the distance between electrodes in a half-period:

$$V_L = 2\nu d$$

if $\nu = 6\text{kHz},\ d = 4\text{mm}$,

$$V_L = 2 \times 6 \times 10^3 \times 4 \times 10^{-3} = 48 \text{ m/sec}$$

In air at STP, $V_S = 331$ m/sec. This is a mach number, $M \approx .15$

The best case is if the ions are produced rapidly enough that they are convected away only when the convection velocity is equal to the ion drift velocity in the electric field,

$$V_H \approx V_{di} \approx \mu_i E_{rms} = \frac{e V_{rms}}{M \nu_{ci} d}$$

For <u>helium</u>, $V_{rms} \simeq 6$ kV, $\nu_{ci} = 6.8 \times 10^9$ Hz, $d = 4$mm

$V_H \approx 5270$ m/sec

The speed of sound at STP in helium is 965 m/sec, for a Mach number $M \approx 5.5$ <u>in Helium</u>

RESPONSE TO TRANSIENT CONDITIONS

1. If the plasma layer suddenly goes off, how quickly will the plane decelerate?

2. Will any such deceleration cause the plane to "crash" in mid-air?

3. If the plasma layer is turned on too suddenly, will the plane accelerate or go out of control?

4. Can the plasma layer be sustained in rain? In fog? In snow?

5. How much power will be required to sustain the plasma layer in precipitation?

ENVIRONMENTAL CONCERNS

1. How much ozone and NO_x will be produced at sea level?

2. Will the production of ozone and NO_x be harmful?

3. Is there any way to minimize or eliminate ozone or NO_x production in air?

4. Will concentrations of ozone and NO_x exceed OSHA guidelines at airports or in aircraft?

5. Will concentrations of ozone and NO_x at low altitudes exceed regional EPA guidelines?

6. How much ozone and NO_x will be produced at flight altitude?

7. Is high altitude ozone and NO_x beneficial or detrimental?

8. Might the world aircraft fleet make a useful contribution to closing the "ozone hole", shielding the ground from UV radiation, and counteracting the damage done by CFC's?

ECONOMIC AND SOCIAL ISSUES

1. Will the drag reduction pay the energy cost of generating the plasma layer?

2. What additional weight of RF and power generation equipment will be required?

3. Insulated strip or adaptive electrodes may be retrofitted to existing aircraft, making it unnecessary to develop new aircraft containing exotic technologies.

4. Can ordinary passengers be persuaded to board an aircraft that glows in the dark?

Plasma-Related Research Tasks

1. Develop database for collision frequencies at one atmosphere.
2. Develop plasma electron number density diagnostic.
3. Develop electron kinetic temperature diagnostic.
4. Confirm theory for ion-trapping frequency band for uniform plasma.
5. Confirm power density dependence on V_{rms}, ν_o.
6. Develop a theory relating plasma polarization (electron <u>and</u> ion trapping) to filamentation.
7. Optimize V_{rms}, ν_o, and electrode geometry for the production of a surface plasma.
8. Investigate surface plasma manipulation by peristaltic wave driving.

SUMMARY AND RESULTS

- We have successfully generated a plasma surface layer in air at one atmosphere on a 5cm diameter simulated aircraft fuselage.
- This surface layer is subject to an electrostatic body force of the same magnitude as the RMS turbulent fluctuations.
- The surface plasma layer is as thick or thicker than the turbulent aerodynamic boundary layer.
- The skin friction on a commercial aircraft accounts for half of its power requirements in level flight.
- The energy cost of generating the plasma layer is from 0.1% to 1% of the skin friction power.
- The plasma surface layer is not blown away by a M = 0.10 airstream, and quickly recovers from a water spray ("rain").

REFERENCES RELATED TO ONE ATMOSPHERE GLOW DISCHARGE PLASMA

1. Von Engle, A.; Seeliger, R.; and Steenbeck, M.: On the Glow Discharge at High Pressure. Zeit. fur Physik, Vol. 85 (1933) pp. 144-160.

2. Kanazawa, S; Kogoma, M.; Moriwaki, T.; and Okazaki, S.: Stable Glow Plasma at Atmospheric Pressure, J. Physics D., Vol. 21 (1988) pp. 838-840.

3. Yokoyama, T.; Kogoma, M.; Moriwaki, T.; and Okazaki, S.: The Mechanism of the Stabilization of Glow Plasma at Atmospheric Pressure, J. Physics D., Vol. 23 (1990) pp. 1125-1128.

4. Kanda, N.; Kogoma, M.; Jinno, H.; Uchiyama, H.; and Okazaki, S.: Atmospheric Pressure Glow Plasma and its Application to Surface Treatment and Film Deposition Paper 3.2-20, Proc. 10th International Symposium on Plasma Chemistry, Vol. 3 (1991) pp. 3.2-201 to 3.2-204.

5. Roth, J. R.; Liu, C.; and Laroussi, M.: Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure. Paper 5P-21, Proc. 1992 IEEE International Conference on Plasma Science, Tampa, FL, IEEE Catalog No. 92-TH0460-6, ISBN 0-7803 0716-X (1992). pp. 170-171.

6. Liu, C.; Chen, D.; and Roth, J. R.: Characteristics of a Steady-State, Low-Power Glow Discharge at Atmospheric Pressure. APS Bulletin Vol. 37, No. 6 (1992) p. 1563.

7. Liu, C.; Tsai, P.P.-Y.; and Roth, J. R.: Plasma Related Characteristics of a Steady-State Glow Discharge at Atmospheric Pressure. Paper 2P-18, Proc. 1993 IEEE International Conference on Plasma Science, Vancouver, B. C. IEEE Catalog No. 93-CH3334-0, ISBN 0-7803-1360-7 (1993) p. 129.

8. Roth, J. R.; Spence, P. D.; and Liu, C.: Preliminary Measurements of the Plasma Properties of a One Atmosphere Glow Discharge Plasma. APS Bulletin Vol. 38, No. 10 (1993) p. 1901.

9. Roth, J. R.; Wadsworth, L. C.; Spence, P. D.; Tsai, P. P.-Y.; and Liu, C.: One Atmosphere Glow Discharge Plasma for Surface Treatment of Nonwoven Textiles Proc. 3rd Annual TANDEC Conference, Nov. 1-3, Knoxville, TN (1993).

10. Wadsworth, L. C.; Roth, J. R.; Tsai, P. P.-Y.; and Spence, P. D.: "Fiber Surface Modifications Using One Atmosphere Glow Discharge Plasma", Proc. 20th ACS National Meeting, San Diego, CA March 13-18, 1994.

11. Liu, C. and Roth, J. R.: "An Atmospheric Glow Discharge Plasma for Aerodynamic Boundary Layer Control." Paper 1P-26, Proc. 21st IEEE International Conference on Plasma Science, Santa Fe, NM, June 6-8, 1994 IEEE Catalog No. 94CH3465-2, ISBN 0-7803-2007-7 (1994) p. 97-98.

12. Spence, P. D. and Roth, J. R.: "Electrical and Plasma Characteristics of a One Atmosphere Glow Discharge Plasma Reactor." Paper 1P-25, Proc. 21st IEEE International Conference on Plasma Science, Santa Fe, NM, June 6-8, 1994 IEEE Catalog No. 94 CH3465-2, ISBN 0-7803-2007-7 (1994) p. 97.

13. Tsai, P. P.-Y.; Wadsworth, L. C.; Spence, P. D.; and Roth, J. R.: "Nonwoven Surface Modification Using One Atmosphere Glow Discharge Plasma." Proc. INDA Conf. on Fundamental Research, 1994.

14. Liu, C. and Roth, J. R.: "Applications of the One Atmosphere Glow Discharge Plasma to Illumination and Aerodynamic Boundary Layer Control" APS Bulletin Vol. 39, No. 7 (1994) p. 1730.

15. Tsai, P. P.-Y.; Wadsworth, L. C.; Spence, P. D.; and Roth, J. R.: "Surface Modification of Nonwoven Webs Using One Atmosphere Glow Discharge Plasma to Improve Web Wettability and Other Textile Properties." Proc. 4th Annual TANDEC Conference, Nov. 14-16, 1994, Knoxville, TN (1994).

16. Roth, J. R. (1995): Industrial Plasma Engineering: Volume I-Principles. Institute of Physics Press, Bristol, U.K. ISBN 0-7503-0318-2.

17. Roth, J. R. and Ku, Y.: "Surface Cleaning of Metals in Air with a One Atmosphere Uniform Glow Discharge Plasma," Submitted to 22nd IEEE International Conference on Plasma Science, June 5-8, 1995, Madison, WI.

18. Liu, C. and Roth, J. R.: "Boundary Layer Control by a One Atmosphere Uniform Glow Discharge Plasma Layer," Submitted to the 22nd IEEE International Conference on Plasma Science, June 5-8, 1995, Madison, WI.

19. Roth, J. R.: Industrial Plasma Engineering: Volume II-Applications. Institute of Physics Press, Bristol, U.K. (to be published April, 1997).

20. Roth, J. R.; Tsai, P. P.; and Liu, C.: "Steady-State, Glow Discharge Plasma" U.S. Patent No. 5,387,842 February 7, 1995.

APPENDIX E

Archival Publications

APPENDIX E

Surface Modifications of Nonwoven Webs Using One Atmosphere Glow Discharge Plasma to Improve Web Wettability and Other Textile Properties

by

Peter P.Y. Tsai, Larry C. Wadsworth and Paul D. Spence

Textiles and Nonwovens Development Center (TANDEC)
University of Tennessee
Knoxville, Tennessee 37996 USA

and

J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
College of Engineering

Abstract

In industrial applications, a steady-state glow discharge capable of operating at one atmosphere would allow many plasma-related surface modification processes to be carried out under production line conditions, rather than in expensive vacuum systems which enforce batch processing. In this paper, we report some encouraging results from the plasma surface treatment of PP meltblown nonwoven fabrics and a PE film which were conducted in the UTK one atmosphere glow discharge plasma reactor. In this reactor, we have generated a large volume (up to 2.4 liters), low power (less than 150 watts) steady state glow discharge plasma in a parallel plate configuration with square electrodes 21.6 centimeters on a side, each covered with a 3.2 millimeter thick insulating pyrex surface. The plates are set up in an enclosed box which makes it possible to control the working gas used, and the spacing between the plates can be varied. This reactor is energized by a custom-made high impedance RF power supply capable of supplying up to 5 kilowatts of RF power at RMS voltages up to 10 kV, and over a frequency range from 1 KHz to 100 KHz. Exposure of a wide variety of polymer fabrics has shown that the wettability, wickability, printability, and surface contact angle of the materials were significantly changed in a direction which may lead to new uses for these materials.

Proc. 4th Annual TANDEC Conference, Nov. 14-16, 1994
Knoxville, TN.

Introduction

The field of industrial plasma engineering has grown in recent decades to encompass a wide variety of manufacturing processes with cash flows of several billions of dollars each year. These uses of plasma are motivated by its ability to accomplish industrially relevant results more efficiently and cheaply than competing processes; by its ability to perform tasks which can be accomplished in no other way; and by its ability to accomplish results without producing large volumes of waste material or toxic byproducts. At the UTK Plasma Science Laboratory, we have recently developed (refs. 1 to 5) a steady state glow discharge plasma reactor which is capable of operating at atmospheric pressure. This one atmosphere glow discharge plasma reactor will make it possible to expose fabrics and polymer films to the active species from a glow discharge plasma without the capital and operating expenses associated with vacuum systems, and without the requirement for batch processing, usually enforced by the exposure of materials to plasmas generated in vacuum systems (ref. 6).

The practical advantages of plasma exposure of textiles have been documented by Rakowski (ref. 7), who compared two processes used to achieve the printability of wool toe (partially processed wool fibers). One process used a conventional chlorination process, and the second used a new process based on the exposure of wool toe to a low pressure plasma. Rakowski's process for achieving the printability of wool cloth using low pressure plasma exposure (ref. 7) is accomplished in the apparatus shown schematically in Figure 1. Wool toe is fed continuously into a vacuum chamber operating at pressures of 2 to 6 torr, where a glow discharge plasma provides active species to which the wool is exposed. A novel feature of this approach is the continuous feeding of the wool toe into and out of the vacuum system through several differential stages of vacuum pumping.

Rakowski has compared this low pressure plasma surface treatment process with the conventional chlorination process and finds that the low pressure plasma modification of 120 tonnes per year of wool saves large quantities of water, chemicals, and electrical energy, as indicated on Table 1. These large savings are possible since the plasma process does not produce large volumes of waste or toxic byproducts. Rakowski finds, in addition, that the chlorination process requires 7 KWH per kilogram of wool, but the low pressure plasma treatment process requires only 0.3-0.6 KWH per kilogram of wool, most of this power being required to operate the vacuum pumps. The above discussion illustrates several advantages of low pressure plasma processing over conventional treatment of textiles to improve their printability. The plasma process is more energy efficient, and does not produce toxic byproducts or large volumes of waste materials. This discussion also illustrates the potential advantages of conducting plasma surface treatments at one atmosphere, as opposed to low pressures which require a vacuum system. If no vacuum pumping were required, the data of Table I indicate that wool could be treated at an energy cost dominated by the power required to maintain the plasma, about 5-15% of the vacuum pumping power.

Whether at one atmosphere or at low pressure, plasmas achieve their surface treatment effects as a result of the interaction of one or more active species from the plasma with the surface of interest. These active species are more chemically reactive and more energetic than the species associated with conventional chemical processing. These active species may include ultraviolet photons, which are capable of breaking chemical bonds; and photons in the visible part of the spectrum, which can produce a positive surface charge by the photoelectric effect. A second major class of active species from plasma are charged particles, which include electrons that either recombine on the surface or build up a surface charge; ions which may be produced by ionization events, attachment, or charge exchange in the plasma; and free radicals or other charged molecular fragments such as OH^- resulting from plasma chemical reactions. A third major class of active species is neutral particles,

which can include very reactive atoms such as monatomic fluorine, oxygen, or other atomic fragments; atoms or molecules in excited atomic states; and highly reactive molecular fragments, including monomers produced in the plasma. Most of these active species are rarely present or much less dense in ordinary chemical reactors, and their high energy levels make possible surface treatment effects which can be achieved only with difficulty if at all with conventional chemical processing.

The One Atmosphere Glow Discharge Plasma Reactor

The generation of plasma at one atmosphere is not a recent development. Electrical arcs have been used at one atmosphere since the early 19th Century for various industrial processes, as has the more recently developed plasma torch (ref. 1, 6). These uses rarely include the surface treatment of materials, since the energy density and power flux in such plasmas is so high that surface treatment would be difficult without accompanying surface damage. The generation of low power density plasmas at one atmosphere also is not new. Filamentary discharges between parallel plates in air at one atmosphere have been used in Europe to generate ozone in large quantities for the treatment of public water supplies since the late 19th century. Such filamentary discharges, while useful for ozone production, are of limited utility for the surface treatment of materials, since the plasma filaments tend to puncture or treat the surface unevenly. The properties of a glow discharge plasma at high pressures, including one atmosphere in air and hydrogen, was reported by von Engle et al. in 1933 (Ref. 8). These discharges were initiated at low pressure (thus requiring a vacuum system), required temperature control of the electrodes, and appear too unstable for routine industrial use.

More recently, a group affiliated with Sofia University in Japan (refs. 9-11) has reported the generation of both filamentary and steady state glow discharge plasmas at one atmosphere of pressure in gases which include helium, and argon with an admixture of acetone. Similar work later originated independently in the UTK Plasma Science Laboratory at the University of Tennessee in Knoxville (refs. 2-5).

A schematic of the one atmosphere glow discharge plasma reactor system developed at the UTK Plasma Science Laboratory is shown in Figure 2. The reactor volume is bounded by two plane, parallel plates across which an RF electric field is imposed. This voltage has an amplitude of kilovolts per centimeter, and frequencies in the kilohertz range. The electric fields must be strong enough to electrically break down the gas used, and are much lower for helium and argon than for atmospheric air. The RF frequency must be in the right range, discussed below, since if it is too low, the discharge will not initiate, and if it is too high, the plasma forms filamentary discharges between the plates. Only in a relatively limited frequency band will the atmospheric glow discharge plasma reactor form a uniform plasma without filamentary discharges.

The parallel electrode plates constituting the reactor are enclosed in a plexiglass container. The principal function of this container is to control the composition of the operating gas used during operation at one atmosphere. As indicated in Figure 2, the reactor has a metal median screen, which may be grounded through a current choke, that is located midway between the two parallel electrode plates. This screen provides a rigid surface which supports the material to be treated, and the holes in the screen allow a gas flow from the top half of the plexiglass box to the bottom half. The top and bottom half of the box are divided by a horizontal partition which supports the metal screen and bisects the volume of space defined by the two parallel plates. The holes in the metal screen provide the only route by which gas fed into the top half of the chamber can flow to the bottom half. This flow of gas through the fabric being treated on the midplane screen is intended to enhance the contact of active species from the plasma not only with the surface of the fabric being exposed, but also with the surfaces of fibers in the interior of the fabric.

The two parallel electrode plates shown on Figure 2 are driven by a power amplifier capable of operation from 0 to 10 kilovolts RMS, over frequencies from less than one kHz

to 100 kHz. This amplifier is capable of producing 5 kW of RF power, far beyond the requirements of the test plasma, which rarely exceed 100 watts. The supply gas is sampled from the exhaust line and leaked into a vacuum system with a mass spectrometer. The two copper electrode plates are 21.6 cm square, and the surfaces in contact with the plasma are covered with a 3.2 mm thick Pyrex insulating plate. The median screen is an uninsulated electrical conductor, and may be grounded or allowed to float electrically. Operating the plasma reactor with the median screen grounded (either directly or through a current choke) makes it possible to reduce the maximum voltage in the plasma reactor chamber to half that which would otherwise be required if one of the two electrode plates were grounded. In addition, keeping the median screen at ground potential also allows the treated materials to remain at ground potential.

The plasma diagnostics utilized in this paper include a mass spectrometer, which draws a sample of gas from the exhaust gas of the plasma reactor through a needle valve and into a vacuum system, where the gas composition is monitored by a quadruple mass spectrometer. Additional diagnostics include monitoring the floating potential of the median screen, the power and power density absorbed by the plasma, and monitoring the voltage and current waveforms on the electrodes with a digital oscilloscope.

Theory Of The Uniform Operating Regime

The electric fields employed in the one atmosphere glow discharge plasma reactor are only a few kilovolts per centimeter, values usually too low to electrically break down the background gas. Gases such as helium and argon will break down under such low electric fields, however, if the positive ion population is trapped between the two parallel plates, while at the same time the electrons are free to travel to the insulated electrode plates where they recombine or build up a surface charge. The most desirable uniform one atmosphere glow discharge plasma is therefore created when the applied frequency of the RF electric field is high enough to trap the ions between the median screen and an electrode plate, but not so high that the electrons are also trapped.

If the RF frequency is so low that both the ions and the electrons can reach the boundaries and recombine, the plasma will either not initiate or form a few coarse filamentary discharges between the plates. If the applied frequency is in a narrow band in which the ions oscillate between the median screen and an electrode plate, they do not have time to reach either boundary during a half period of oscillation. If the more mobile electrons are still able to leave the plasma volume and impinge on the boundary surfaces, then the desirable uniform plasma is produced. If the applied RF frequency is still higher so that both electrons and ions are trapped in the discharge, then the discharge forms the filamentary plasma.

We now propose an approximate theory which yields a relationship between the electrode spacing, the RMS electrode voltage, and the applied frequency which results in trapping ions but not electrons between the two plates, and produces the desired uniform one atmosphere glow discharge plasma. On Figure 3 is a schematic of the upper chamber of the one atmosphere glow discharge plasma reactor. The lower boundary of this space is the midplane screen, the floating potential of which should remain near ground if the RF power supply output is connected as a push-pull circuit to the two electrodes with a grounded center tap. In the data reported herein, the median screen was grounded through an inductive current choke. In the configuration of Figure 3, a Cartesian coordinate system is applied as shown, with the applied electric field in the x-direction. The maximum amplitude of the electric field between the grounded median screen and the upper electrode is E_0, and the separation of the screen from the electrodes is the distance d. The median screen, with an exposed sample on it, is assumed not to allow ions through the median plane from the upper chamber to the lower, or vice-versa.

The electric field between the electrodes shown on Figure 3 is given by

$$E = (E_0 \sin \omega t, 0, 0). \tag{1}$$

It is assumed that the one atmosphere glow discharge operates in a magnetic field free plasma. The equation of motion for the ions or electrons between the two plates is given by a Lorentzian model, in which the electrons and ions collide only with the neutral background gas and, on each collision, give up all the energy they acquired from the RF electric field since the last collision to the neutral gas. The equation of motion for the ions or electrons in the Lorentzian model is given by

$$\mathbf{F} = m\,\mathbf{a} = -m\,\nu_c\,\mathbf{v} - e E, \tag{2}$$

where the first term on the right hand side is the Lorentzian collision term, according to which the momentum mv is lost with each collision that occurs with a collision frequency ν_c. The x component of Eq. 2 is given by

$$m\frac{d^2x}{dt^2} + m\,\nu_c\frac{dx}{dt} = eE_0 \sin\omega t, \tag{3}$$

where the electric field E from Eq. 1 has been substituted into the right hand side of Eq. 2. The general solution to Eq. 3 is

$$x = C_1 \sin\omega t + C_2 \cos\omega t, \tag{4}$$

where the constants C_1 and C_2 are given by

$$C_1 = -\frac{eE_0}{m}\frac{1}{(\omega^2+\nu_c^2)}, \tag{5}$$

and

$$C_2 = -\frac{\nu_c\, eE_0}{\omega\, m}\frac{1}{(\omega^2+\nu_c^2)}. \tag{6}$$

The one atmosphere helium glow discharge is operated at frequencies between $\omega/2\pi \approx 1$ and 30 KHz, where, for helium at one atmosphere (Ref. 1),

$$\nu_{ci} \approx 6.8 \times 10^9 \text{ ion collisions/sec.}, \tag{7a}$$

and

$$\nu_{ce} \approx 1.8 \times 10^{12} \text{ electron collisions/sec.} \tag{7b}$$

The collision frequency for ions and electrons given by Eqs. 7a and 7b is much greater than the RF frequency, $\nu_c >> \omega$. The relation $\nu_c >> \omega$ for ions and electrons, implies that C_2 is much greater than the constant C_1, or

$$C_2 \approx -\frac{eE_0}{m\,\omega\,\nu_c} >> C_1. \tag{8}$$

The time dependent position of an ion or an electron in the electric field between the plates is given by substituting Eq. 8 into Eq. 4, to obtain

$$x(t) \approx -\frac{e E_0}{m\,\omega\,\nu_c} \cos \omega t. \tag{9}$$

The RMS displacement of the ion or electron during a half cycle is given by

$$x_{rms} = \frac{2}{\pi} \frac{eE_0}{m\,\omega\,\nu_c} \text{ meters}. \tag{10}$$

If ν_0 is the driving frequency, in Hertz, and V_{rms} is the RMS voltage applied to the plates, then the radian RF frequency is given by

$$\omega = 2\pi\nu_0, \tag{11}$$

and the maximum electric field between the plates can be approximated by the maximum voltage V_0 appearing between them,

$$E_0 = \frac{V_0}{d} = \frac{\pi V_{rms}}{2d}. \tag{12}$$

If the charge in question moves across the discharge width from the median plane to one of the electrode plates during one full cycle, then we may write

$$x_{rms} \leq \frac{d}{2}. \tag{13}$$

Equation 13 states that the RMS displacement of the particle has to be less than half the clear spacing in order to have a buildup of charge between the plates. In the geometry shown in Figure 3, the distance d is identified with the distance between the grounded median screen and the energized electrode. Substituting Eqs. 11 to 13 into Eq. 10 yields the relationship

$$\frac{d}{2} \approx \frac{e V_{rms}}{2\pi m \nu_0 \nu_c d}. \tag{14}$$

If we now solve for the critical frequency ν_0 above which charge buildup should occur in the plasma volume, we have

$$\nu_0 \approx \frac{e V_{rms}}{\pi m \nu_c d^2} \text{ Hz}. \tag{15}$$

In Eq. 15, the collision frequency ν_c is given by Eqs. 7a or 7b for ions or electrons, respectively, at one atmosphere, and the RMS voltage is that which bounds the upper and lower limit of the uniform discharge regime.

Power Density Of The One Atmosphere Uniform Glow Discharge Plasma

Commercial applications of the one atmosphere uniform glow discharge plasma to the surface treatment of materials require power densities high enough to produce useful

amounts of plasma active species, but not so high as to damage such sensitive materials as fabrics and polymer films. Our experience in the UTK Plasma Science Laboratory thus far suggests that a useful range of plasma power densities is from 10 milliwatts/cm^3 to perhaps 200 milliwatts/cm^3, although the high limit might be considerably greater if a rapidly-moving web passed through a higher power density plasma with a total exposure (or dwell) time short enough to avoid damage.

To understand the factors which determine plasma power density, we extend the above analysis as follows. The work done on a single electron between the plates by the RF electric field is given by

$$W = \mathbf{F}.\mathbf{dx} = eE(t)dx \quad (J). \tag{16}$$

The power delivered to this electron is

$$p = \frac{dW}{dt} = eE(t)\frac{dx}{dt} = eE(t)\dot{x} \qquad (W\,/\,\text{electron}). \tag{17}$$

Taking the derivative of Eq. 4,

$$\dot{x} = C_1\,\omega\cos\omega t - C_2\,\omega\sin\omega t. \tag{18}$$

Substituting Eq. 1 for E(t) and Eq. 18 into Eq. 17, one obtains

$$p = e\,E_o\omega C_1\sin\omega t\cos\omega t - e\,E_o\,\omega C_2\sin^2\omega t \tag{19}$$

The average power per unit volume is found by multiplying Eq. 19 by the electron density, and integrating over a cycle of oscillation, $\omega t = 2\pi$. The first term of Eq. 19 averages to zero, and the remaining term is

$$\overline{P} = n_e\,\overline{p} = \frac{n_e e\,E_o\,\omega C_2}{2\pi}\int_0^{2\pi}\sin^2\omega t\,d(\omega t)$$

$$= \frac{n_e e\,E_o\,\omega C_2}{2} \quad (W\,/\,m^3). \tag{20}$$

Substituting Eq. 6 for C_2, Eq. 20 becomes

$$\overline{P} = -\frac{n_e e\,E_o\,\omega}{2} \times \frac{\nu_c e\,E_o}{\omega m(\omega^2+\nu_c^2)} = -\frac{e^2E_o^2\nu_c\,n_e}{2m(\omega^2+\nu_c^2)}. \tag{21}$$

In the one atmosphere uniform glow discharge plasma reactor, the driving frequency is typically 1-10 kilohertz, while ν_c is gigahertz for ions, and terahertz for electrons. Thus, $\nu_c >> \omega$, and Eq. (21) may be approximated as

$$\overline{P} \approx -\frac{n_e\,e^2\,E_o^2}{2m\,\nu_c}. \tag{22}$$

Using Eq. 12 to write the maximum electric field E_O in terms of the rms applied voltage in this parallel plate geometry, one obtains Eq. 22 in the form

$$\overline{P} = - \frac{n_e e^2}{2m\,\nu_c} \frac{\pi^2 V_{rms}^2}{4\,d^2} = - \frac{\pi^2 e^2 V_{rms}^2}{8m\,\nu_c d^2} \qquad (W/m^3). \tag{23}$$

This relation predicts a power density proportional to the square of the applied voltage. In experimental data presented previously (ref. 12), a cubic dependence on voltage was observed.

The relative power delivered to the electron and ion populations can be calculated by rationing Eq. 23 for the ion and electron populations,

$$\frac{\overline{P}_i}{\overline{P}_e} = \frac{m\,\nu_{ce}}{M\,\nu_{ci}}, \tag{24}$$

where m and M are the electron and ion mass, and ν_{ce} and ν_{ci} the electron and ion collision frequencies, respectively. Using the collision frequencies from Eqs. 7a and 7b, and the relative masses, we obtain for helium,

$$\frac{\overline{P}_i}{P_e} = \frac{1.8 \times 10^{12}}{4 \times 1837 \times 6.8 \times 10^9} = .036 \tag{25}$$

Thus for helium, most of the power is delivered to the electron population, where it is most effective in producing active species.

The One Atmosphere Glow Discharge Plasma

The range of parameters over which we have operated the one atmosphere glow discharge plasma reactor at the UTK Plasma Science Laboratory is given in Table II. The nominal pressure at which this discharge has been operated is one atmosphere. The variation of several torr shown in Table II is not intended to represent the day-to-day fluctuations of barometric pressure, but the pressure differential across the midplane screen which is intended to drive active species from the upper plasma through the fabric being exposed. The RMS power shown in Table II is the net power delivered to the plasma, less the reactive power which does not appear in the plasma. The total volume of plasma between the two electrode plates is given by

$$S = 0.93\, d(\mathrm{cm}) \text{ liters}, \tag{26}$$

where d is the separation of a plate from the median screen in centimeters.

The power densities shown in Table II are far below those of electrical arcs or plasma torches, but also are several orders of magnitude higher than the power densities associated with some other forms of plasma treatment such as corona discharges. The power densities of the one atmosphere glow discharge plasma are generally low enough not to damage exposed fabrics, but are also enough higher than coronal plasmas used for surface treatment that they should provide far more active species than the latter. The plasma parameters, such as electron kinetic temperature and number density are somewhat speculative at this early stage in our research program. A few results from probing the plasma midplane with a floating Langmuir probe indicates that the plasma, without grounding the midplane screen, will float to positive potentials of several hundred volts.

The ion kinetic temperatures are very likely close to that of the room temperature atoms with which they frequently collide at these high pressures; the electrons apparently remain numerous and energetic enough to excite the neutral background atoms, hence making this a glow discharge. The existence of excited states which emit visible photons implies that the electron population has a kinetic temperature of at least an electron volt. The diagnostic difficulties of measuring plasma parameters at this high pressure are very severe, since ordinary Langmuir probing technique cannot be applied due to the short mean free paths of the electrons compared to a Debye distance. Electron number densities, however, may be measured by microwave interferometric techniques, and this is a line of investigation which we intend to persue.

Fabric Treatment By The One Atmosphere Glow Discharge Plasma Reactor

Experimental

Polypropylene meltblown webs of 3 oz/yd^2 basis weight were treated using one atmosphere glow discharge plasma at different conditions in the range specified in Table II using different working gases. A series of formic acid solution as shown in Figure 4 was prepared to test the critical surface tension of the substrates after plasma treatment. A five-second standard was used to determine the critical surface tension of the substrate, i.e., the surface tension of a formic solution is the critical surface tension of the substrate if a drop of the solution spreads out on the substrate within five seconds. The higher the critical surface tension of the material, the more wettable the material is. The substrate is wettable with water if its critical surface tension is equal or greater than that of water, which is 71.2 dynes/cm at 25^{o}C.

Electron spectroscopy for chemical analysis (ESCA) was used to analyze the chemical elements on the surface of the substrate before and after the plasma treatment. Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) were used to detect the physical surface change on the substrate.

Results and Discussion

Tables III, IV and V show the critical surface tension and its decay with time of 3 oz/yd^2 meltblown PP webs treated by different plasma conditions. Table III illustrates that treatment time is critical to make the webs water-wettable, e.g., sample 5 is not wettable by one minute treatment while samples 6 and 7 are wettable by the treatment of two or three minutes. Sample 1 shows a less wettable web was produced using a mixture of CO_2 and H_2 as working gases than that of using CO_2 alone. The thesis is not quite understood. If oxygen content is important in making the webs wettable, there is a large amount of oxygen in the mixture of CO_2 and H_2 for the ratio of 93:7 to treat Sample 1. Samples 2,3 and 4 in the table show that the webs were less wettable if treated at higher temperatures. It could be that the more wettable groups carboxyl, carbonyl and hydroxyl were further converted into ether or ester which are much less wettable.

Two groups of working gases, CO_2 and $CO_2 + O_2$, were used to treat the webs of Table IV at different electrical and temperature conditions. It is observed that using CO_2 alone at a driving frequency less than 2 kHz would not make the webs wettable while using the mixture of $CO_2 + O_2$ as working gas could make the webs wettable for the treatment of one minute at high temperature, e.g. sample 6. However, the web was not wettable if treated at low temperature for one minute as shown by Sample 1 in the Table.

Table V shows similar results as in Table IV. However, Sample 1 shows that the web was not wettable if treated at low voltage and/or temperature, cf. samples 1,5 of Table V and Sample 6 of Table IV. There are critical voltage, power driving frequency and temperature that make the webs wettable. Table VI shows the six parameters that affect the wettability of the webs. More importantly, they are dependent one another, i.e. if one parameter-changes then one or more other parameters should change.

The wettability decay shown in Figure 5 are the samples of Table III. However, the samples of Tables IV and V had the similar decay trend. The wettability decay began to level off after the treatment of three days. The water-wettable samples of Tables III, IV and V are wettable after the treatment of six months using testing standard of 30 seconds.

Figures 6 and 7 are the ESCA analysis curves of PP untreated and treated meltblown webs. A mixture of He and O_2 was used as working gas in this treatment. The wettability of the treated web lasted for about two weeks and then disappeared. Polypropylene (PP) is a pure hydrocarbon material, which contains no oxygen element. The oxygen content at the peak of 531 eV on the untreated PP came by the contamination from the chamber or other sources since most of the materials are made of polymers which contain oxygen element. There was no increase in oxygen peak in Figure 7 for treated PP. This means that the plasma treatment did not convert hydrocarbon into polar groups. The wettability could possibly come from the polarization of the molecules in PP and the wettability disappeared because of the depolarization of the molecules with time. The depolarization rate depends on the nature of the material properties.

Figures 8 and 9 are another set of ESCA analysis curves of control and treated PP meltblown fabrics, in which a mixture of CO_2 and O_2 was used as plasma working gas. The oxygen peak at 531 eV in Figure 9 shows that there was a chemical reaction that converted hydrocarbon in PP to carbonyl, carboxyl and/or hydroxyl polar groups. The ratio of O1:C1 was 0.01 for untreated PP and 0.193 for treated PP as shown in Table VII. The treated web became wettable by the contribution of polar groups and the wettability was durable because the chemical reaction that converted hydrocarbon to polar groups was irreversible. Furthermore, the molecules were also polarized by the plasma treatment. The polarization also contributed to the web wettability. The initial wettability was high because of the contribution of both polarization and polar groups. The wettability decreased and leveled off with time because the material was depolarized with time and the polar groups stayed without reversible reaction.

The same chemical process held for PE film as shown by ESCA curves in Figures 10 and 11 for untreated and treated PE films. The ratio of O1:C1 was 0.14 for untreated PE and .558 for treated PE film in Table VII. A drop of water had a large contact angle on the untreated film and water drop spreaded out on the treated film as shown in the presentation slide. Figures 12,13,14 and 15 are the SEM photomicrographs of untreated and treated PE films and PP fibers. The change on the whole surface of the film and fibers shows that there was a chemical reaction rather than a microetching on the surface. Microetching is a tiny concave that is a hole dug by the charges. The area that was not dug by the charges should remain a smooth surface.

The AFM pictures that show the surface roughness on the films and fibers agrees with SEM photomicrographs. There was a significant roughness change on the surface after the plasma treatment as shown in figures 16 and 17 for untreated and treated PE films and PP fibers..

Conclusions

We have developed a steady state glow discharge plasma reactor which is capable of operating at one atmosphere in helium, argon, air, carbon dioxide and other gases. This reactor does not require a vacuum system, and only a simple enclosure is needed if one wishes to operate with gases other than atmospheric air. The question of determining the

regime for stable, uniform, steady state glow discharge operation has been approached theoretically. The RF frequency, RMS electrode voltage, and plate spacing d which provide stable operation have been determined. Desirable values of these parameters range between 1 and 10 KV for the RMS electrode-to-electrode potential; 0.5 to 8 KV per centimeter for the RMS electric field; 1 to 10 kHz for the RF driving frequency; and 6mm to 5cm for the plate separation, d.

The voltage-current characteristics of the one atmosphere glow discharge plasma reactor indicate electrical breakdown of the plasma part of the way through each RF cycle; the intensity and duration of the plasma current drawn depend upon the frequency and electric field of the applied RF power. Without an impedence matching network between the RF power amplifier and the plasma reactor, the reactive power usually greatly exceeds the true power actually delivered to the plasma. The power actually delivered to the plasma has a power density that ranges from a few milliwatts per cubic centimeter to several 10's of milliwatts per cubic centimeter, values which are high enough to produce interesting amounts of active plasma species, but at the same time low enough to avoid damaging exposed materials.

The energy of active species produced by this one atmosphere glow discharge plasma is suitable for surface modification of polymer materials. Our first objective is to make a meltblown web have a good affinity for water. Several aspects affect the web wettability, such as pore size, fiber diameter, fiber surface roughness and fiber surface chemical composition. The last aspect is the most important one that affects the fiber surface wettability, because it determines the surface bonding forces with water; i.e. dispersion force, polar force and H-bonding force. In contrast to our previous trial with a higher RF frequency and lower voltage [4], in which more filamentary discharges were produced, no micro damage or micro etching was observed by SEM photomicrographs. However, water wettability was improved. This shows that fiber surface damage or micro etching is not a primary reason for improved wettability of a meltblown webs.

References

1. Roth, J. R.: Industrial Plasma Engineering: Volume I-Principles. Institute of Physics Press, Bristol, U.K. (1994) ISBN 0-7503-0317-4 (to be published April, 1994).

2. Roth, J. R.; Liu, C.; and Laroussi, M.: Experimental Generation of a Steady-State Glow Discharge at Atmospheric Pressure. Paper 5P-21, Proc. 1992 IEEE International Conference on Plasma Science, Tampa, FL, IEEE Catalog No. 92-TH0460-6, ISBN 0-7803 0716-X (1992). pp. 170-171.

3. Liu, C.; Chen, D.; and Roth, J. R.: Characteristics of a Steady-State, Low-Power Glow Discharge at Atmospheric Pressure. APS Bulletin Vol. 37, No. 6 (1992) p. 1563.

4. Liu, C.; Tsai, P.P.-Y.; and Roth, J. R.: Plasma Related Characteristics of a Steady-State Glow Discharge at Atmospheric Pressure. Paper 2P-18, Proc. 1993 IEEE International Conference on Plasma Science, Vancouver, B. C. IEEE Catalog No. 93-CH3334-0, ISBN 0-7803-1360-7 (1993) p. 129.

5. Roth, J. R.; Spence, P. D.; and Liu, C.: Preliminary Measurements of the Plasma Properties of a One Atmosphere Glow Discharge Plasma. APS Bulletin Vol. 38, No. 10 (1993) p. 1901.

6. Roth, J. R.: Industrial Plasma Engineering: Volume II-Applications. Institute of Physics Press, Bristol, U.K. (to be published April, 1996).

7. Rakowski, W.: Plasma Modification of Wool Under Industrial Conditions. Melliand Textilberichte, Vol. 70 (1989) pp. 780-785.

8. Von Engle, A.; Seeliger, R.; and Steenbeck, M.: On the Glow Discharge at High Pressure. Zeit. fur Physik, Vol. 85 (1933) pp. 144-160.

9. Kanazawa, S; Kogoma, M.; Moriwaki, T.; and Okazaki, S.: Stable Glow Plasma at Atmospheric Pressure, J. Physics D., Vol. 21 (1988) pp. 838-840.

10. Yokoyama, T.; Kogoma, M.; Moriwaki, T.; and Okazaki, S.: The Mechanism of the Stabilization of Glow Plasma at Atmospheric Pressure, J. Physics D., Vol. 23 (1990) pp. 1125-1128.

11. Kanda, N.; Kogoma, M.; Jinno, H.; Uchiyama, H.; and Okazaki, S.: Atmospheric Pressure Glow Plasma and its Application to Surface Treatment and Film Deposition Paper 3.2-20, Proc. 10th International Symposium on Plasma Chemistry, Vol. 3 (1991) pp. 3.2-201 to 3.2-204.

12. Roth, J. R.; Wadsworth, L.C.; Spence, P.D.; Tsai, P.P.; and Liu C.: A One Atmosphere Glow Discharge Plasma reactor for Surface Treatment of Nonwoven Fabrics, Book of Papers, TANDEC 3rd Annual Conference, Knoxville, Tennessee, Nov. 1-3, 1994

Tab I

ACHIEVING PRINTABILITY OF WOOLEN CLOTH (Rakowski, Ref. 1)

Compared with "Conventional" chlorination process, the low pressure (2-6 torr) plasma modification of 120 tonnes/year of wool saves:

27,000 m^3	Water
44 Tonnes	Sodium Hypochlorite
16 Tonnes	Sodium Bisulphite
11 Tonnes	Sulphuric Acid
685 MWH	Electrical Energy

The Comparative Energy Costs Are:

Chlorination: 7 kWH/kg wool

Low Pressure Plasma: 0.3-0.6 kWH/kg wool

Power Requirements for 60 kg/hour of wool are:

Low Pressure Plasma: 18-36 kW

Atmospheric Plasma: 1-4 kW

Table II

OPERATING CHARACTERISTICS OF THE ONE ATMOSPHERE GLOW DISCHARGE PLASMA REACTOR

working gas = H_e, H_e + 1-7% 0_2, Ar, Ar + H_e, Ar + 1-7% 0_2

frequency = 1 KHz to 100 KHz

voltage = 1.5 - 9.5 kV_{rms} plate to plate

electrode gap d = 0.8 - 2.5cm

pressure = 760 +15, -5 torr

RMS power = 10 watts to 150 watts

power density = 4 - 120 mW/cm^3

plasma volume = 0.7 - 2.4 liters

Table III Treatment of 3 oz/yd^2 MB webs 1,2,3,4

Sample	Treatment Time (min:sec)	Working Gas	Gas Temp. (^oF)	Critical 3-7-94 17:30	Surface 3-8-94 17:30	Tension 3-9-94 17:30	(dynes/cm) 3-10-94 19:00
1	3:00	CO_2,H_2[a]	71	56.3	54.9	53.5	52.2
2	1:00	CO_2	97	62.8	58.4	56.3	54.9
3	2:00	CO_2	98	64.2	60.5	58.4	54.9
4	3:00	CO_2	95	66.2	60.5	58.4	56.3
5	1:00	CO_2	69	60.5	58.4	54.9	54.9
6	2:00	CO_2	68	71.2	62.8	60.5	58.4
7	3:00	CO_2	70	71.2	70.1	68.0	64.2

Note: 1. Fabric was treated at 00:15 a.m.on 3-7-94 at one atmosphere pressure.
2. Applied voltage = 8.0 KV_{rms}, frequency = 2 KHz
3. Space gap between electrodes = 0.170", Pyrex thickness = 0.125"
4. E_{rms} = 16 KV/cm
a. Volume ratio CO_2:H_2 = 93:7

Table IV Treatment of 3 oz/yd^2 MB webs [1,2]

Sample	Treatment Time (min:sec)	Voltage (KV_{rms})	Freq. (KHz)	Working Gas	Gas Temp. (^oF)	Critical Surface Tension (dynes/cm) 3-8-94 17:30	3-9-94 17:30	3-10-94 19:00
1	1:00	9.32	1.2	CO_2,O_2[a]	70	70.1	60.5	58.4
2	2:00	9.4	1.2	CO_2,O_2[a]	70	71.2	66.2	64.2
3	2:00	9.4	1.2	CO_2,O_2[b]	70	71.2	71.2	68.0
4	3:00	9.4	1.2	CO_2,O_2[b]	72	71.2	71.2	68.0
5	4:00	9.4	1.2	CO_2,O_2[b]	75	71.2	71.2	68.0
6	1:00	9.6	1.2	CO_2,O_2[b]	130	71.2	60.5	58.4
7	2:00	9.4	1.2	CO_2,O_2[b]	130	71.2	60.5	58.4
8	3:00	9.35	1.2	CO_2,O_2[b]	131	71.2	60.5	58.4
9	1:00	9.52	1.2	CO_2	129	58.4	56.3	54.9
10	2:00	9.52	1.2	CO_2	128	58.4	58.4	54.9
11	3:00	9.52	1.2	CO_2	130	58.4	58.4	56.3
12	4:00	8.92	1.5	CO_2	120	60.5	58.4	58.4
13	1:00	8.82	1.5	CO_2	69	58.4	56.3	54.9
14	4:00	8.8	1.5	CO_2	69	60.5	58.4	58.4
15	3:00	8.8	1.5	CO_2	70	60.5	58.4	56.3
16	2:00	8.92	1.5	CO_2	68	58.4	56.3	56.3

Note: 1. Fabrics were treated at 3:15 a.m. on 3-8-94 at one atmosphere pressure.
2. Space gap between electrodes = 0.105", Pyrex thickness = 0.125"
a. Volume ratio $CO_2:O_2$ = 85:15
b. Volume ratio $CO_2:O_2$ = 88.6:11.4

Table V Treatment of 3 oz/yd^2 MB webs [1,2]

Sample	Treatment Time (min:sec)	Voltage (KV_{rms})	Freq. (KHz)	Working Gas	Gas Temp. (^oF)	Critical Surface Tension (dynes/cm) 3-9-94 17:30	Critical Surface Tension (dynes/cm) 3-10-94 19:00
1	1:00	8.8	1.2	CO_2,O_2[a]	127	62.8	58.4
2	2:00	8.8	1.2	CO_2,O_2[a]	129	71.2	60.5
3	3:00	9.8	1.2	CO_2,O_2[a]	132	71.2	60.5
4	3:00	8.8	1.2	CO_2,O_2[a]	140	71.2	58.4
5	1:00	9.4	1.2	CO_2,O_2[a]	102	62.8	60.5
6	2:00	9.4	1.2	CO_2,O_2[a]	102	71.2	66.2
7	3:00	9.4	1.2	CO_2,O_2[a]	102	71.2	66.2
8	3:00	9.4	1.2	CO_2,O_2[a]	90	71.2	64.2
9	4:00	9.4	1.2	CO_2,O_2[a]	107	71.2	64.2

Note: 1. Fabrics were treated at 3:15 a.m. on 3-9-94 at one atmosphere pressure.
2. Space gap between electrodes = 0.105", Pyrex thickness = 0.125"
a. Volume ratio $CO_2:O_2$ = 94.6:5.4

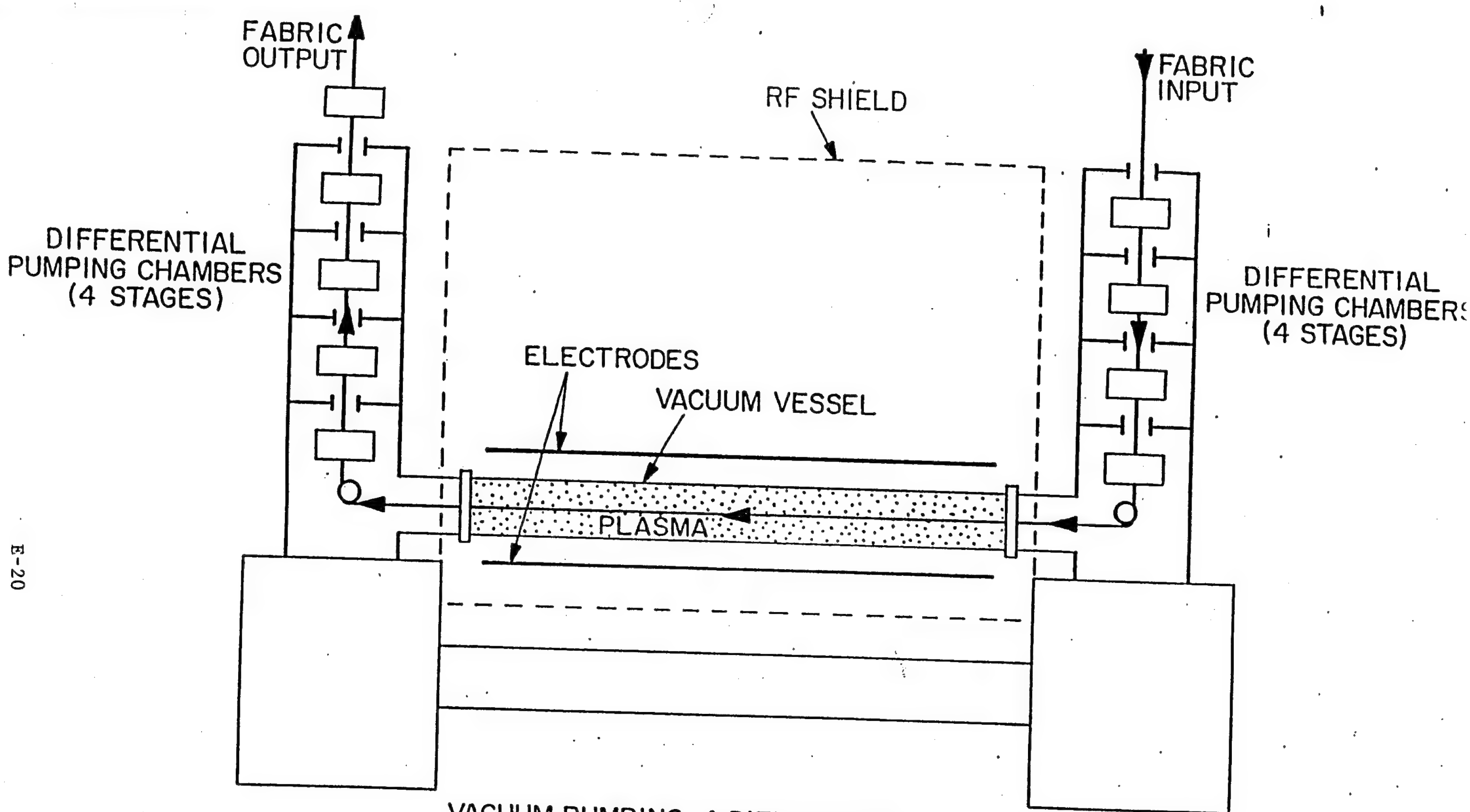
Table VI

Six Factors Affecting Wettability

- Voltage
- Frequency
- Gap between electrodes
- Working gas
- Treating time
- Gas temperature

Table VII ESCA Analysis Table

sample	Carbon 1s			Oxygen 1s			Ratio (O1:C1)
	Count rate (kc/s)	Count time (minute)	Count no.	Count rate (kc/s)	Count time (minute)	Count no.	
PE Untreated	0.351	12.56	618180	5.844	12.56	86584	0.140
PE Treated	1.275	12.56	1432864	7.665	12.56	799383	0.558
PP Untreated	2.077	29.31	4068212	7.601	29.31	41445	0.010
PP Treated	2.569	29.31	3904294	10.212	29.31	752271	0.193



VACUUM PUMPING: 4 DIFFERENTIAL STAGES
VACUUM PRESSURE: 2-6 TORR
PRODUCTION RATE: 60 kg/HOUR OF WOOL
TOTAL SURFACE AREA: 30,000 m^2/HOUR

APPARATUS FOR LOW PRESSURE PLASMA TREATMENT OF WOOL (W. RAKOWSKI REF. I)

FIGURE I

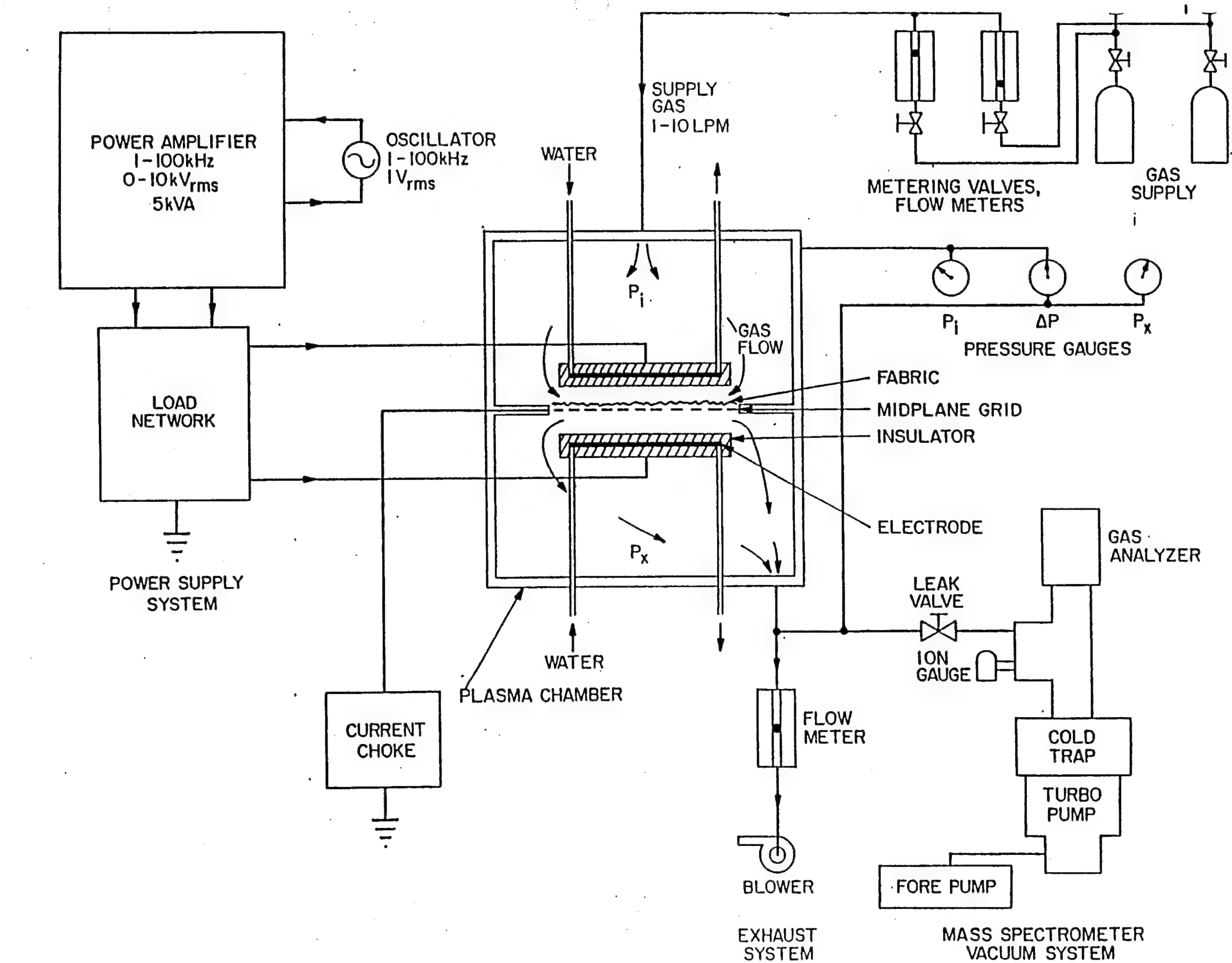

POWER AMPLIFIER
1-100kHz
0-10kV$_{rms}$
5kVA
OSCILLATOR
1-100kHz
1V$_{rms}$
LOAD
NETWORK
POWER SUPPLY
SYSTEM
CURRENT
CHOKE
WATER
SUPPLY
GAS
1-10LPM
P_i
GAS
FLOW
P_x
WATER
PLASMA CHAMBER
METERING VALVES,
FLOW METERS
GAS
SUPPLY
P_i
ΔP
P_x
PRESSURE GAUGES
FABRIC
MIDPLANE GRID
INSULATOR
ELECTRODE
GAS
ANALYZER
LEAK
VALVE
ION
GAUGE
COLD
TRAP
TURBO
PUMP
FLOW
METER
BLOWER
FORE PUMP
EXHAUST
SYSTEM
MASS SPECTROMETER
VACUUM SYSTEM

FIGURE 2

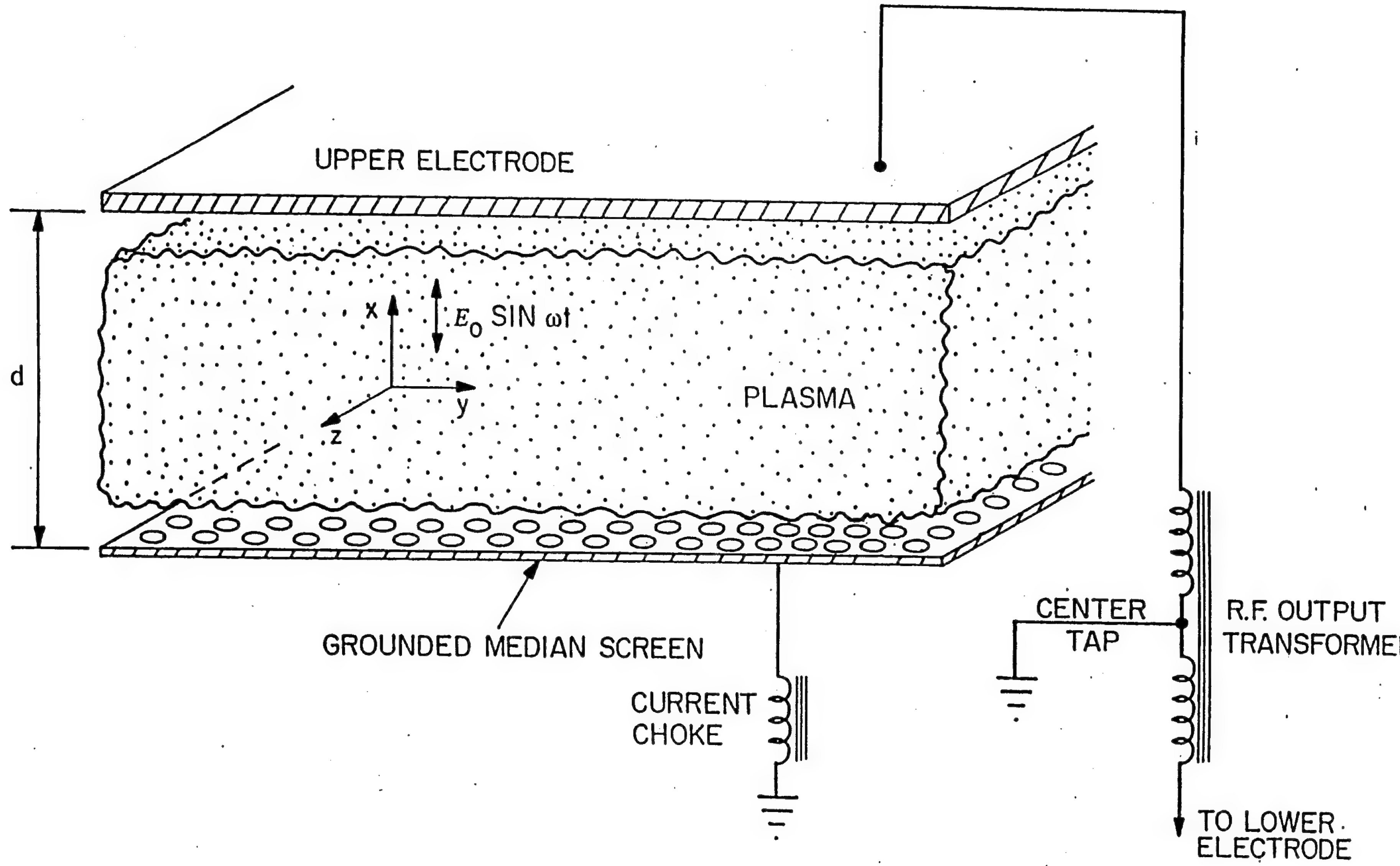

UPPER ELECTRODE
d
x
y
z
E_0 SIN ωt
PLASMA
GROUNDED MEDIAN SCREEN
CURRENT
CHOKE
CENTER
TAP
R.F. OUTPUT
TRANSFORMEI
TO LOWER
ELECTRODE

Figure 3

Figure 4 Surface tension versus concentration

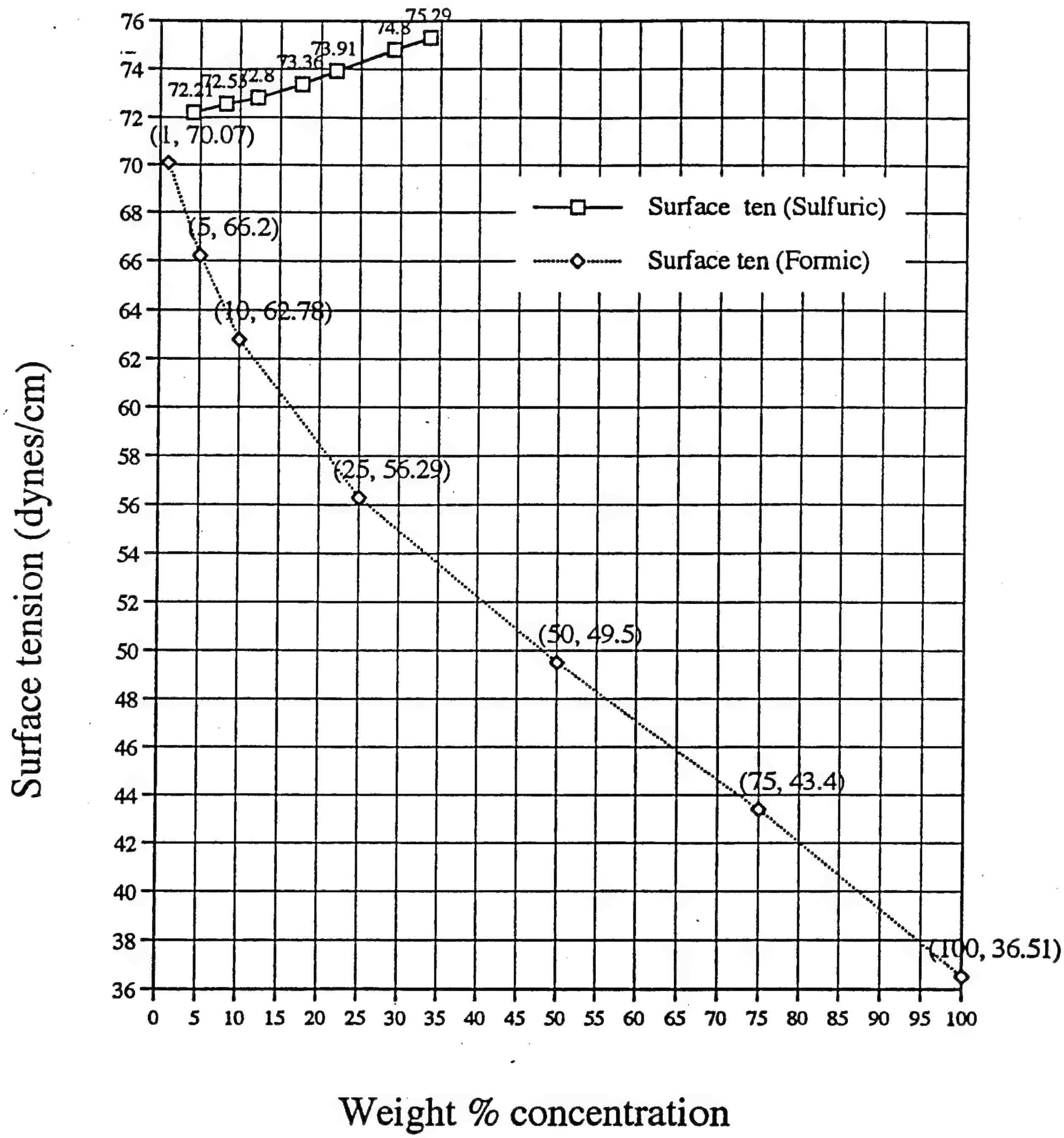
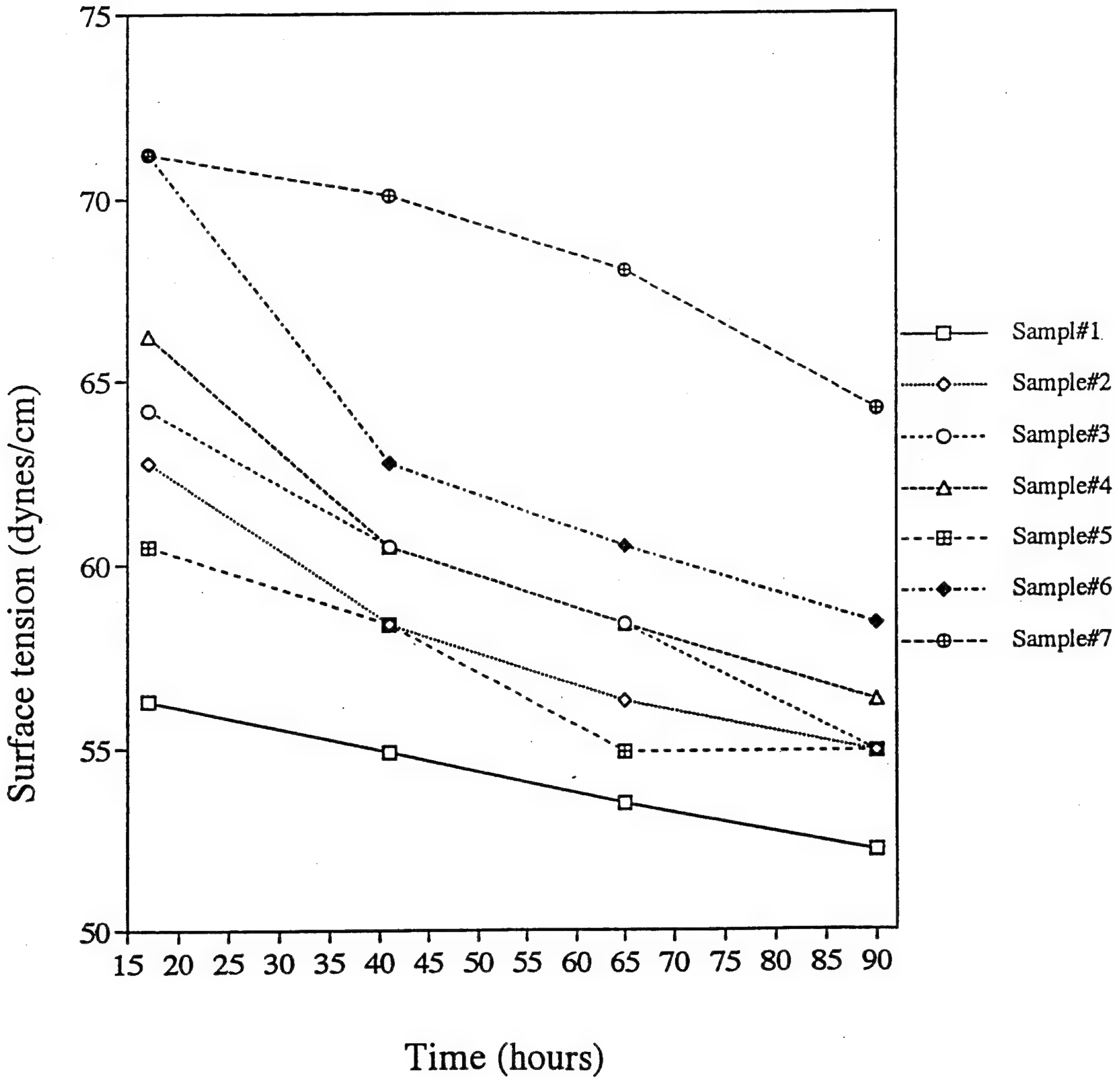


Figure-5 Decay of critical surface tension with time (from Table 2)



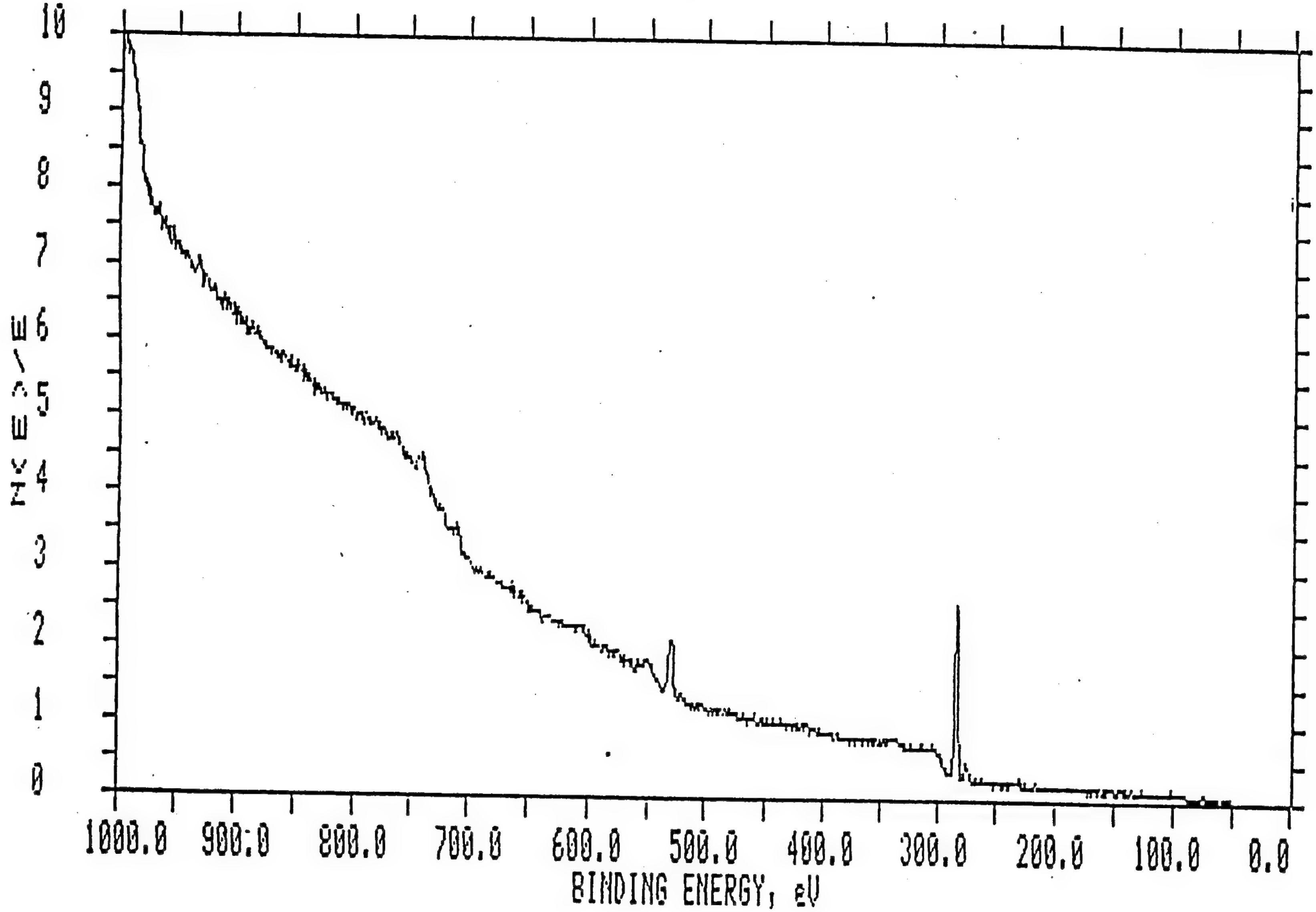


Figure 6 ESCA curve of untreated meltblown 850 MFR PP web

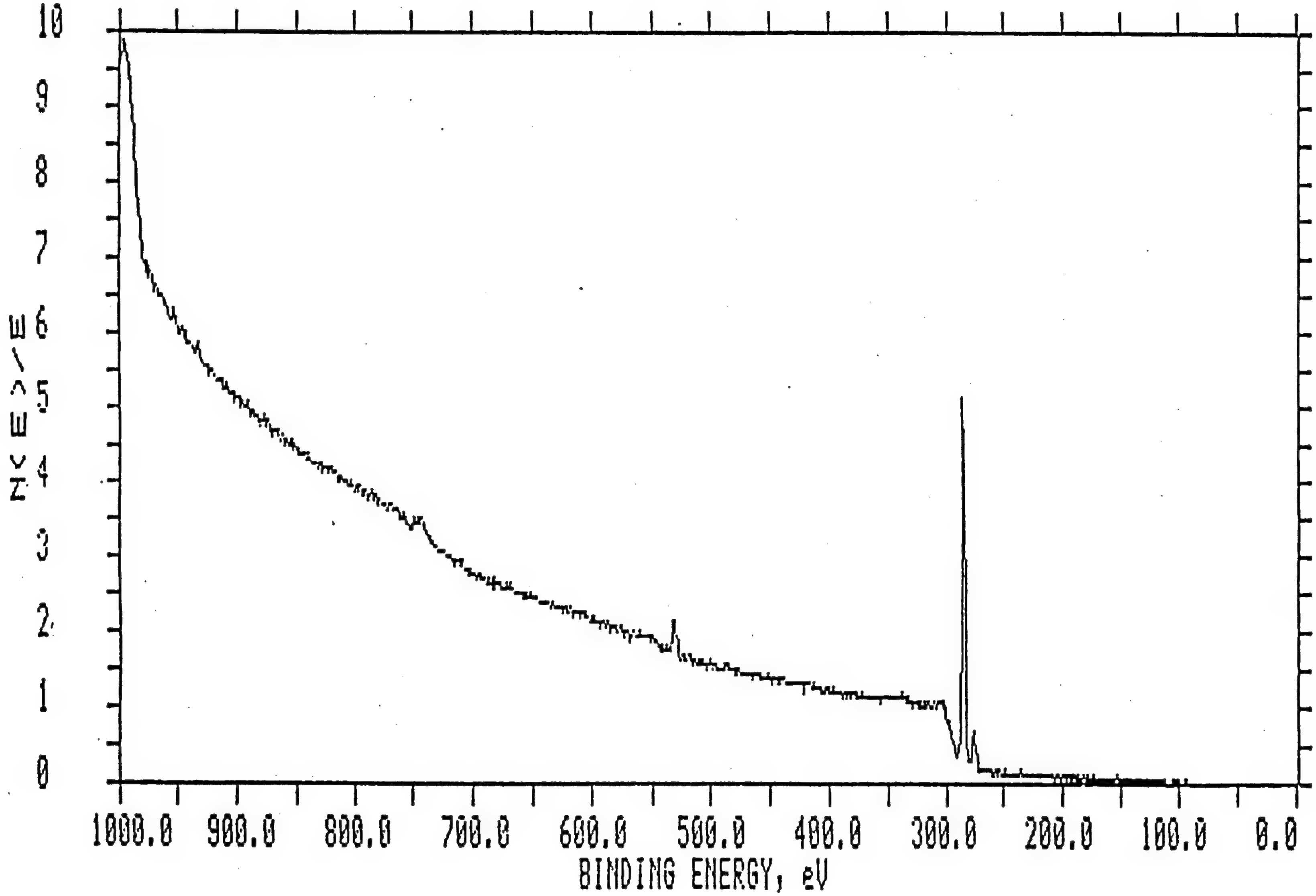


Figure 7 ESCA curve of $He+O_2$ treated meltblown 850 PP web

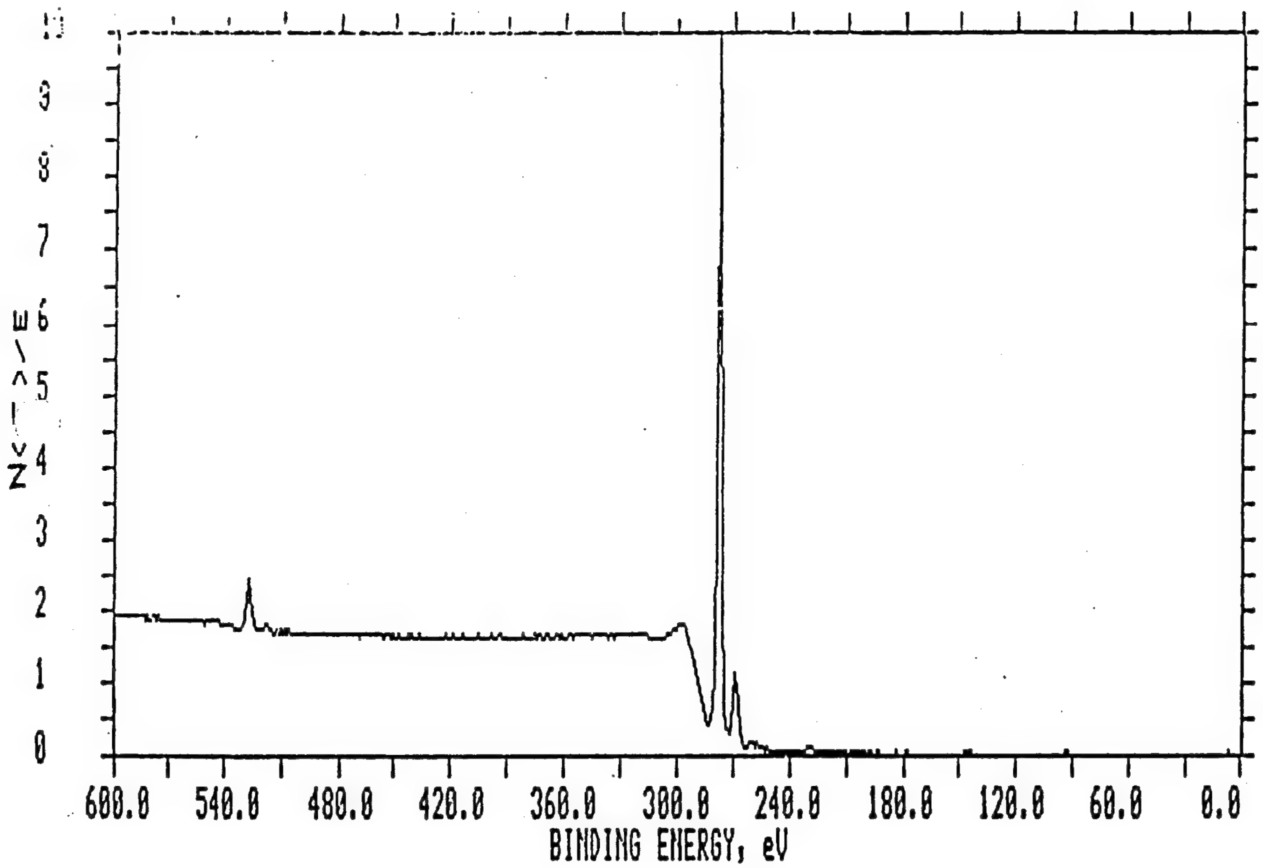


Figure 8 ESCA curve of untreated meltblown 450 MFR PP web

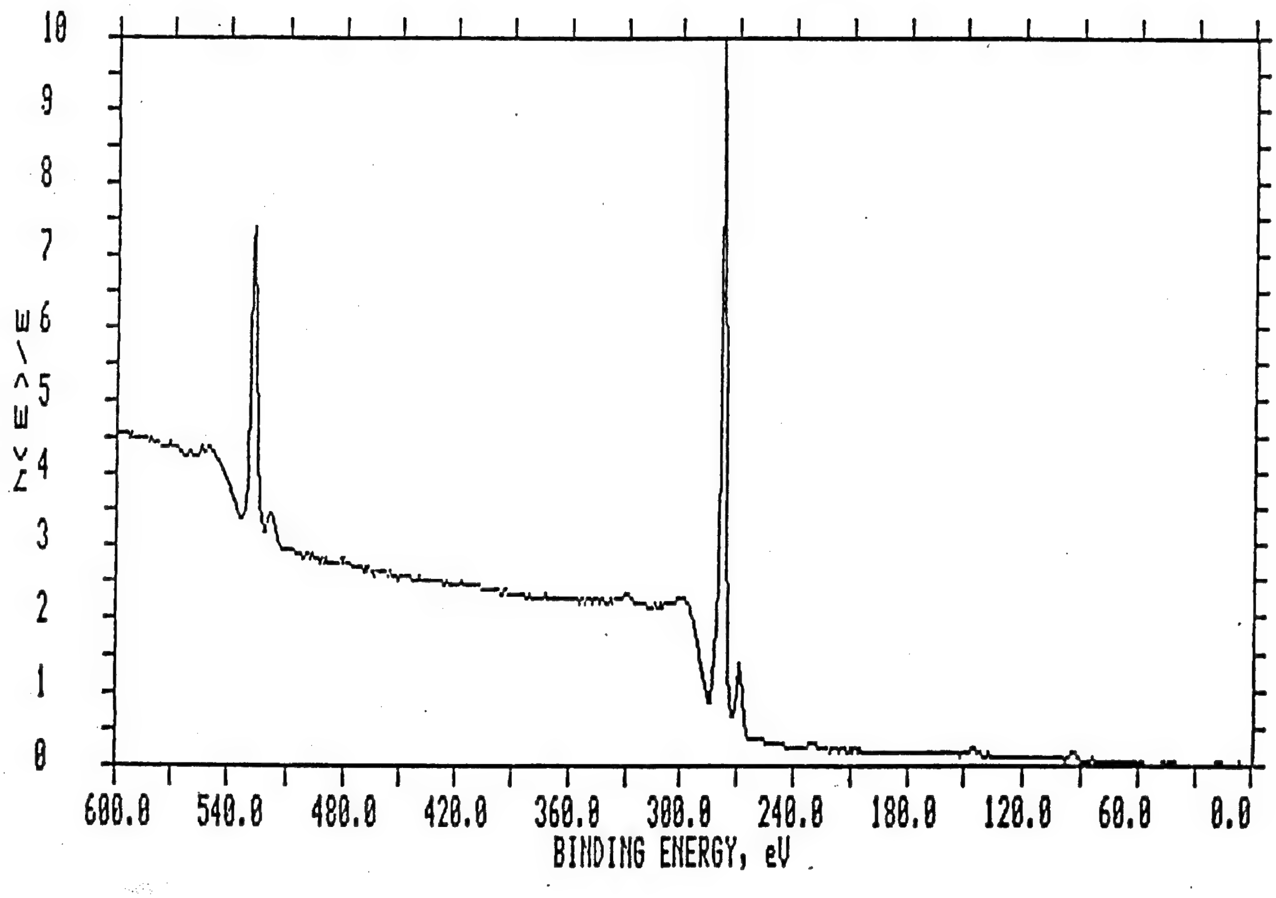


Figure 9 ESCA curve of treated meltblown 450 MFR PP web

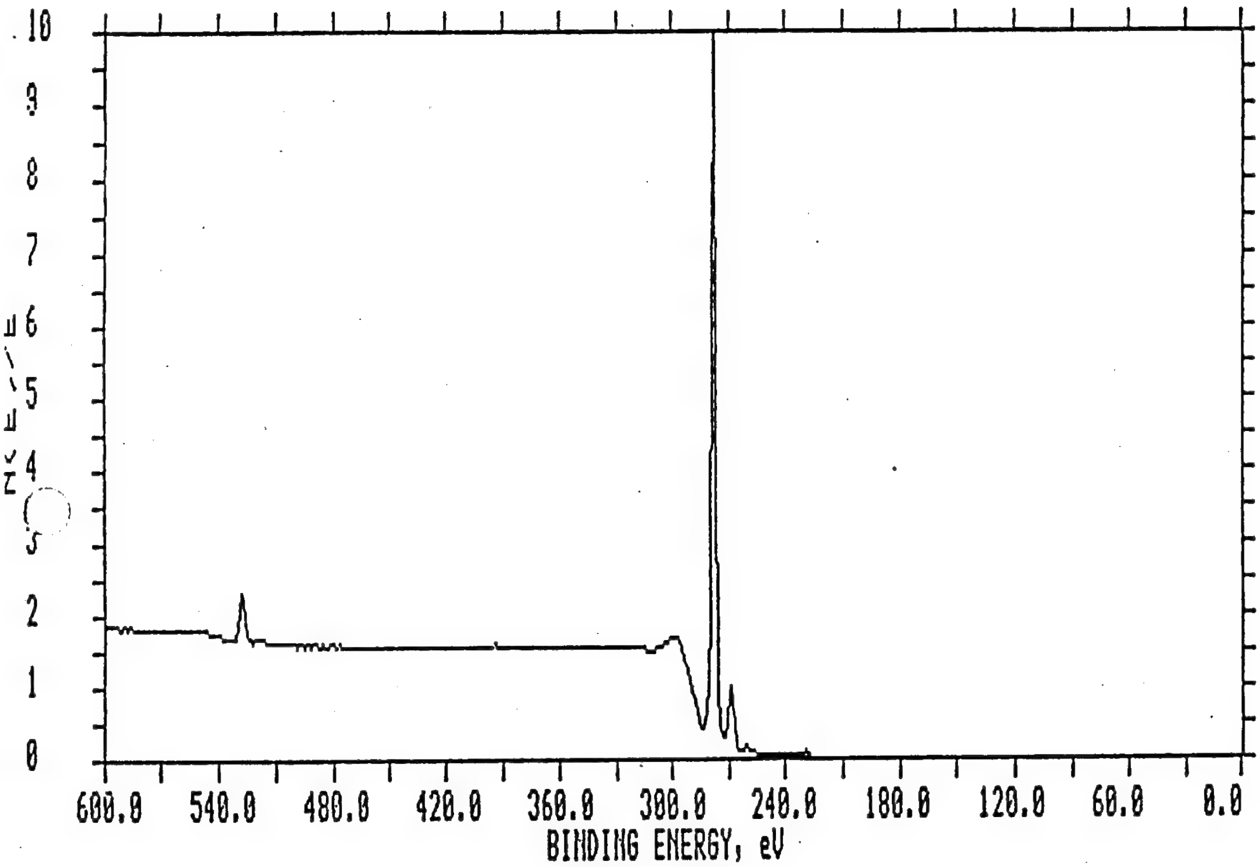


Figure 10 ESCA curve of untreated PE film

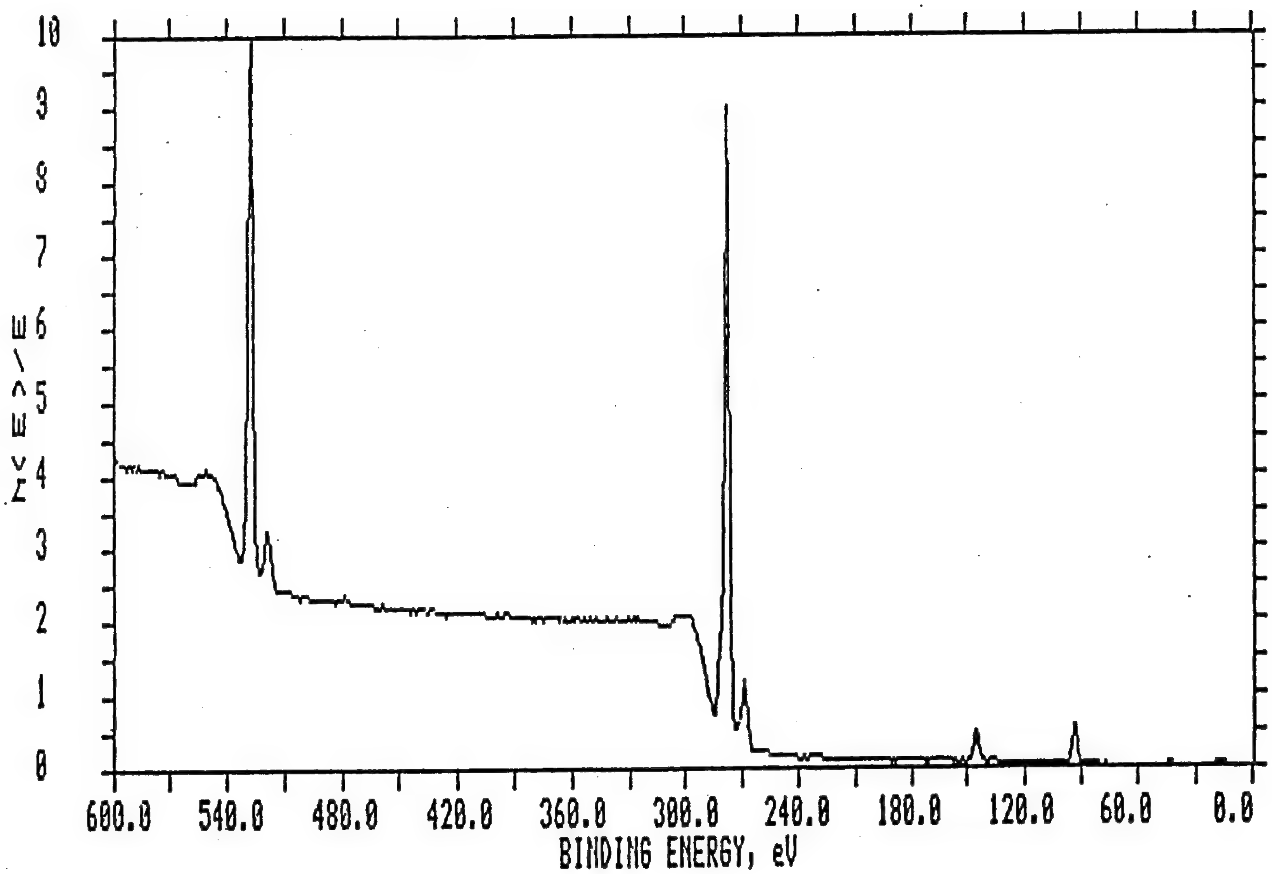


Figure 11 ESCA curve of treated PE film

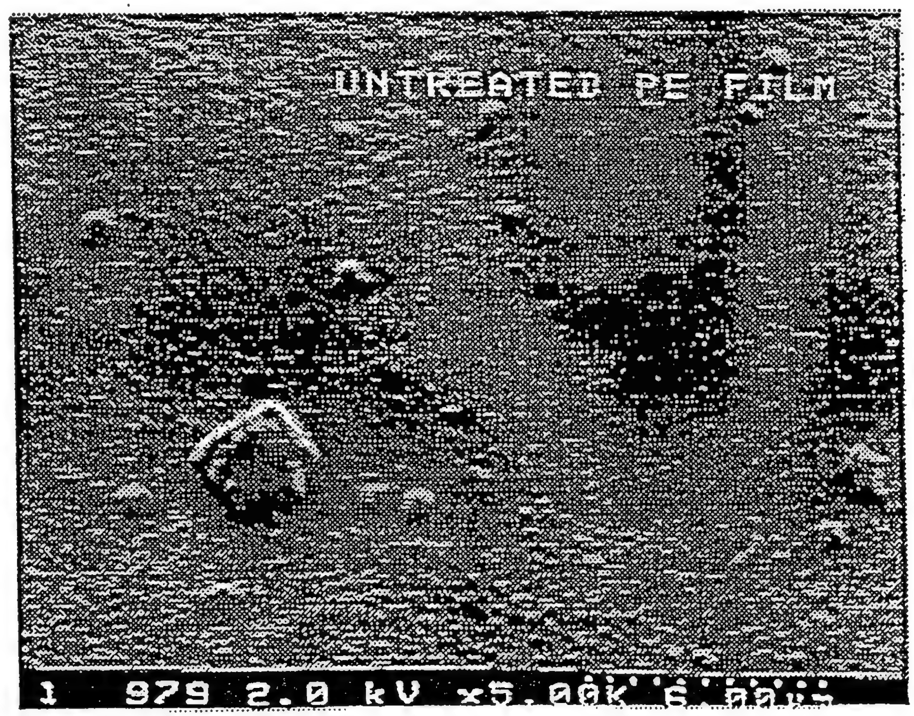


Figure 12 SEM photomicrograph of untreated PE film

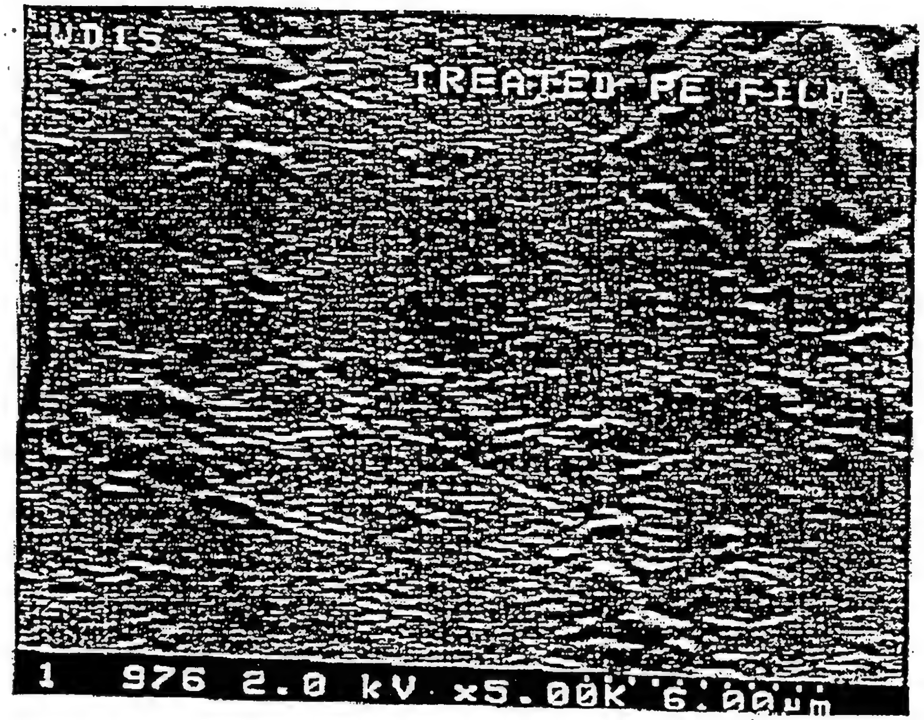


Figure 13 SEM photomicrograph of treated PE film

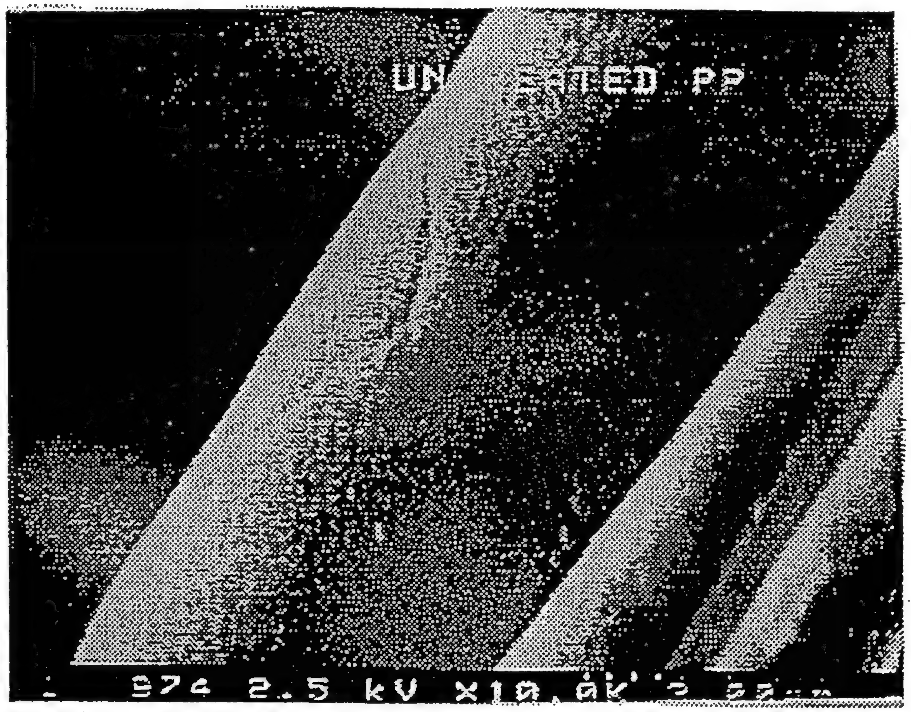


Figure 14 SEM photomicrograph of untreated PP fibers

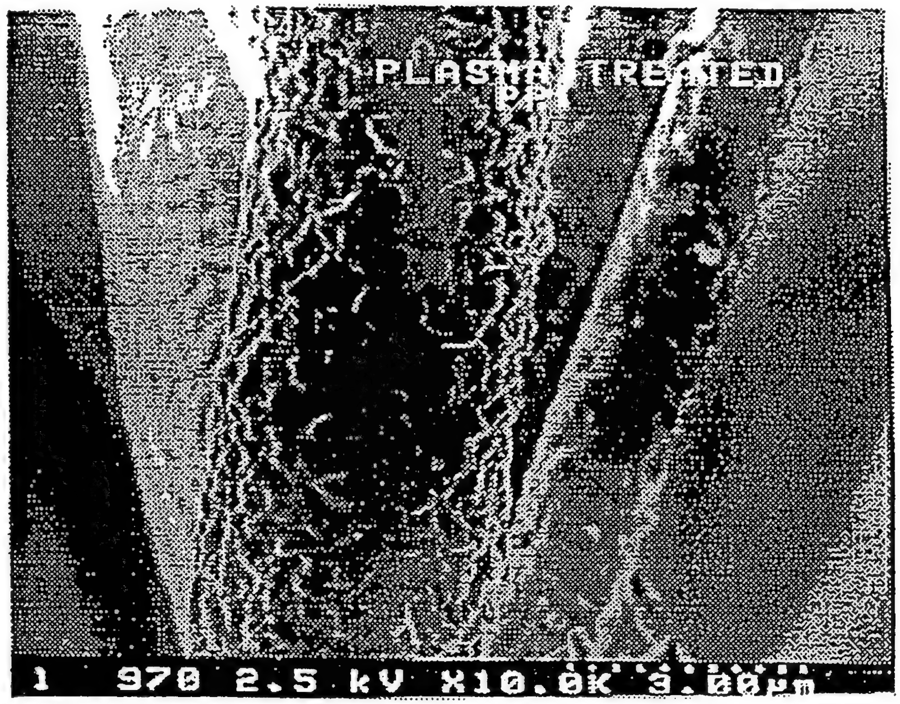
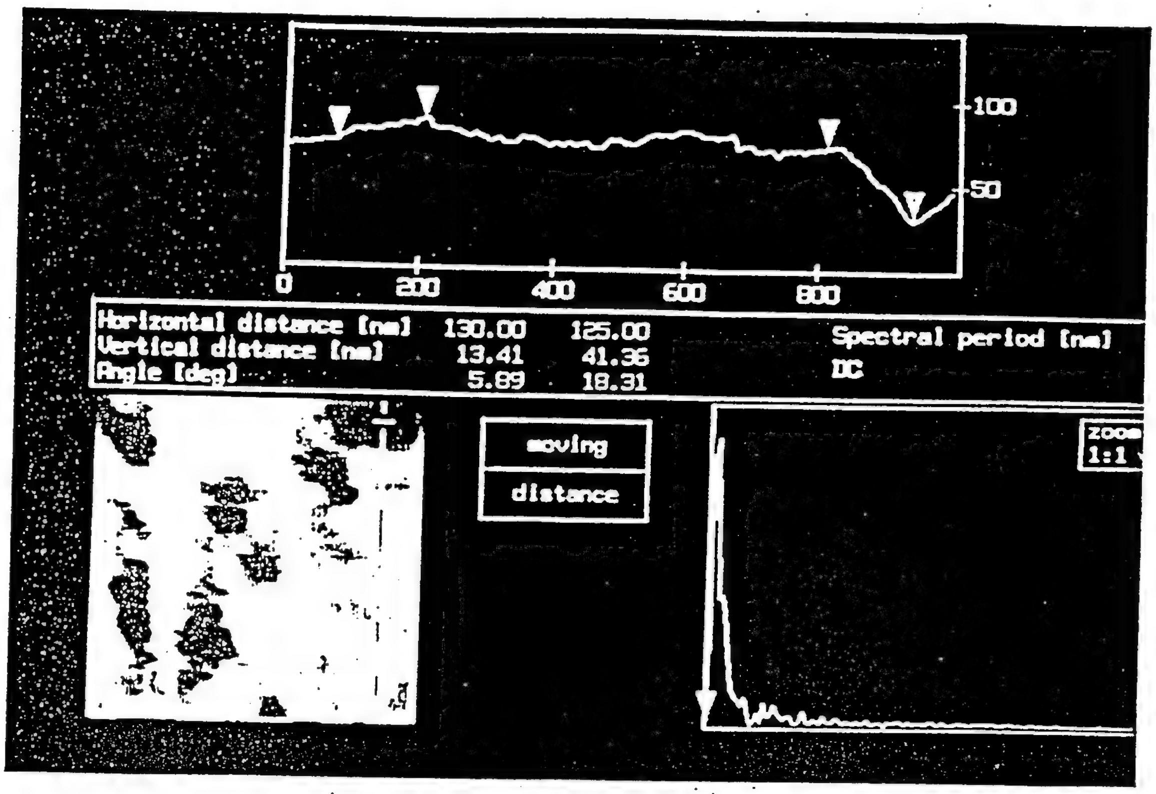


Figure 15 SEM photomicrograph of treated PP fibers



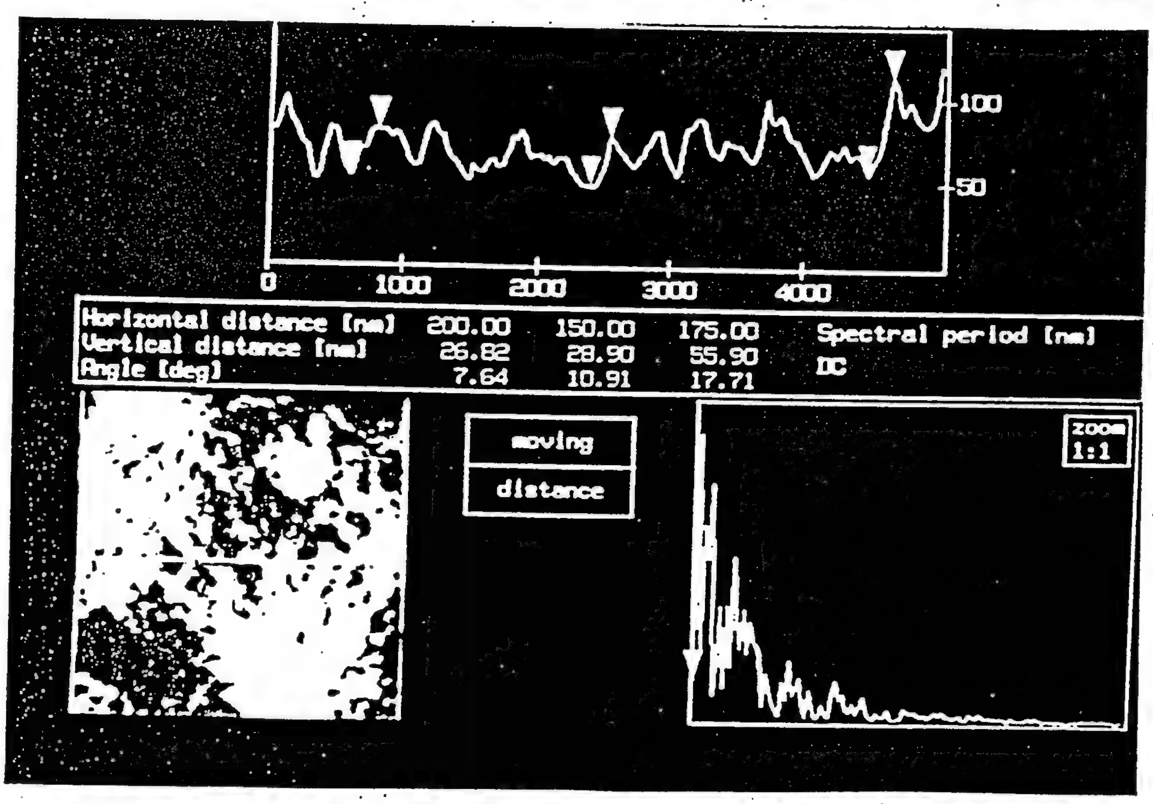
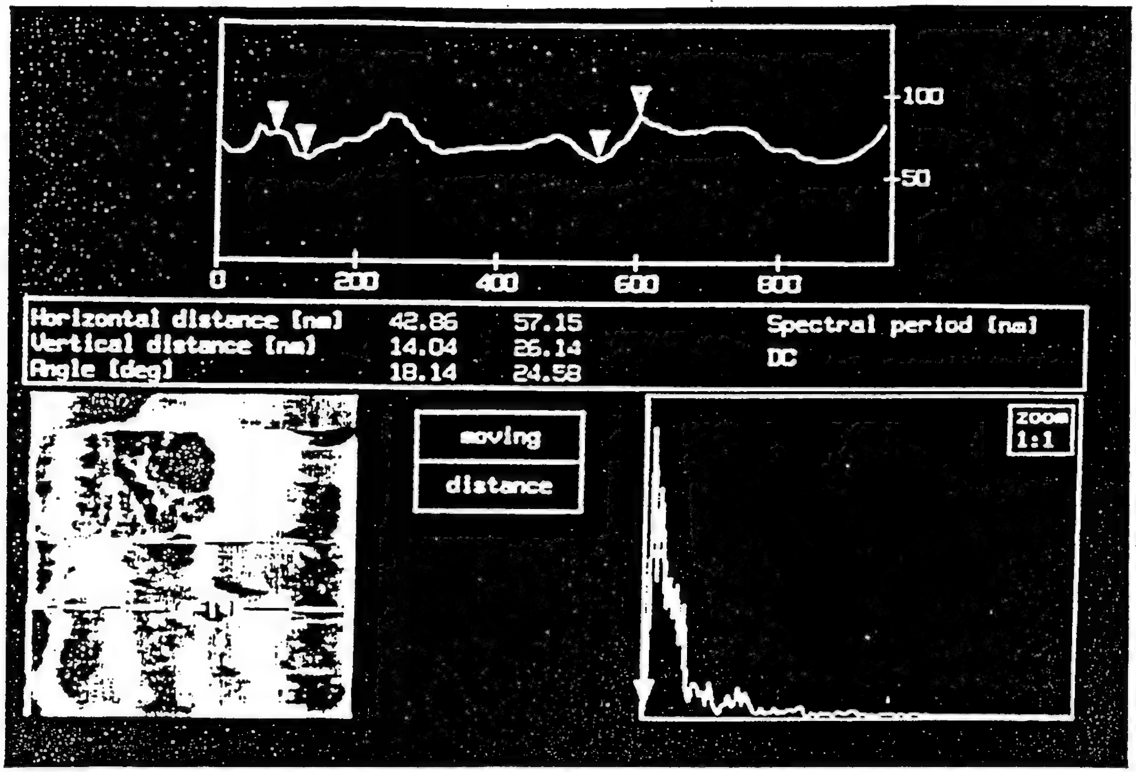


Figure 16 AFM surface roughness meaurement of untreated (above) and treated (bottom) PE film



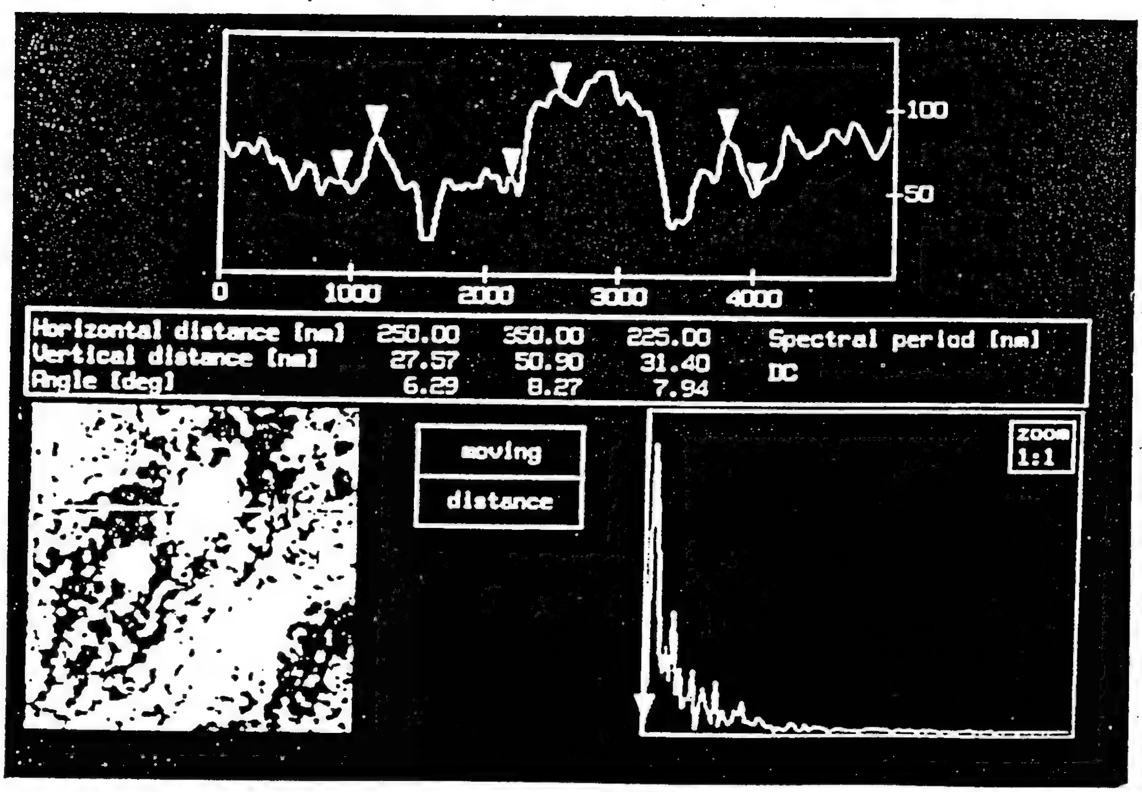


Figure 17 AFM surface roughness meaurement of
untreated (above) and treated (bottom) PP fibers

BALL LIGHTNING: WHAT NATURE IS TRYING TO TELL THE PLASMA RESEARCH COMMUNITY

SPHERICAL PLASMA CONFIGURATIONS

KEYWORDS: *spherical configurations, ball lightning, plasma confinement*

J. REECE ROTH *University of Tennessee*
409 Ferris Hall, Knoxville, Tennessee 37996-2100

Received December 20, 1993
Accepted for Publication January 7, 1994

Ball lightning has been extensively observed in atmospheric air, usually in association with thunderstorms, by untrained observers who were not in a position to make careful observations. These chance sightings have been documented by polling observers, who constitute perhaps 5% of the adult U.S. population. Unfortunately, ball lightning is not accessible to scientific analysis because it cannot be reproduced in the laboratory under controlled conditions. Natural ball lightning has been observed to last longer than 90 s and to have diameters from 1 cm to several metres. The energy density of a few lightning balls has been observed to be as high as 20 000 J/cm^3, well above the limit of chemical energy storage of, for example, TNT at 2000 J/cm^3. Such observations suggest a plasma-related phenomenon with significant magnetic energy storage. If this is the case, ball lightning should have very interesting implications for fusion research, industrial plasma engineering, and military applications, as well as being of great theoretical and practical interest to the plasma research community.

INTRODUCTION

In the closing years of the twentieth century, very few natural phenomena on the human scale remain inaccessible to scientific analysis. Ball lightning is such a phenomenon. Although the existence of ball lightning has been generally acknowledged by the scientific community since the death of Richmann, who was killed by ball lightning in the summer of 1753 in St. Petersberg, Russia, during an attempt to extend Benjamin Franklin's kite experiment, no one has yet been able to reproducibly create ball lightning in the laboratory. As a result, the scientific study of ball lightning under controlled, reproducible conditions has not been possible.

Ball lightning is defined as a glowing, self-luminous sphere moving slowly or floating in the atmosphere and is usually associated with lightning strokes or thunderstorm activity. Ball lightning is much more rare than a lightning stroke, and its occurrence at random times and places has made its scientific study very difficult. In the United States, ball lightning has been observed by ~5% of the adult U.S. population at some time in their lives. What is now known about the characteristics of ball lightning is the product of a large body of random observations by untrained observers, many of whom were participants in a frightening experience. This database is useful, however, because it provides important constraints on theoretical models of ball lightning.

Perhaps because the phenomenon of ball lightning is a scientific mystery, the literature on ball lightning is voluminous. Ball lightning has been placed in the context of ordinary atmospheric electrical and lightning discharges by Uman[1] and by Singer.[2] Two additional books entirely on the subject of ball lightning have been written by Singer[3] and by Barry.[4] These latter two books contain some of the better documented sightings of ball lightning, summarize information on its characteristics, discuss inconclusively various theoretical models for ball lightning, and report attempts to reproduce ball lightning artificially under controlled conditions.

The characteristic observation of ball lightning occurs after a lightning stroke or during a thunderstorm ~80% of the time. The lightning ball can be from 1 cm to 1.5 m in diameter, and almost all colors of the visible spectrum have been reported. Lightning balls have been known to last from a few seconds to >150 s; they appear to have neutral buoyancy and either sink very slowly to the ground or float above the ground at a constant height; they rarely make noise until they suddenly disappear, with a noise that ranges from a barely audible popping sound to a major explosion. An ozone-like or sulfurous odor is sometimes associated with ball lightning, and when it terminates, its behavior ranges

from simply winking out of existence to a major explosion that can do more damage than a hand grenade. In those cases in which lightning balls have come in contact with human observers, the results range from a barely perceptible tingling sensation, through stunning, to death.

Attempts have been made to obtain quantitative information about ball lightning by detailed polling of adult members of the public who have seen ball lightning at some time in their lives. Typically, such a poll will consist of a first round in which the staff of a major national laboratory or other institution will be asked whether they have ever seen ball lightning. Those who reply affirmatively are asked to fill out a more detailed questionnaire, designed to elicit every type of qualitative or quantitative information that might be available from an untrained observer without scientific instruments. The results of several of these polls are cited in Refs. 3 and 4. During the 1960s, surveys of the staff at two national laboratories in the United States provided a large database of ball lightning observations. At the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, McNally circulated questionnaires to 15 923 staff members, which elicited 498 reports of ball lightning observations.[5] Also in the 1960s, Rayle surveyed 4400 staff members at the National Aeronautics and Space Administration's Lewis Research Center in Cleveland, Ohio, and obtained 180 reports of ball lightning observations.[6]

Attempts have been made for at least a century to create ball lightning in the laboratory. Barry[4] describes an experiment conducted circa 1910 in Norway that involved shorting the terminals of a 10-MW direct-current (dc) generator, which produced long-lived, free-floating electrical discharges that were photographed and had characteristics similar to those of ball lightning. In Refs. 3 and 4 it is reported that many observations of a ball lightning phenomenon were made in World War II submarines. In these submarines, switching an inductive load (an electric motor that drove the propellers) connected to a large battery bank, which typically involved 200-V dc and currents of 15 000 A, produced electrical arcs in the switchgear that occasionally generated small luminous spheres a few centimetres in diameter. The properties of these spheres were indistinguishable from those of ball lightning. Such ball lightning also was generated in experiments at the Philadelphia Naval Shipyard. More recently, Alexeff and Rader[7] have reported looped electrical sparks in the Holifield National Accelerator at ORNL, which may be a predecessor to the formation of a ball lightning-like electrical discharge. In none of these experiments on ball lightning–like phenomena were quantitative observations made beyond attempts at photography.

In relatively recent experiments involving radio-frequency (rf) excitation, Powell and Finkelstein (see Refs. 3 and 4) were able to generate a glowing, steady-state ball of plasma at, or slightly below, atmospheric pressure in laboratory experiments but only with steady-state rf energy input. More recently, Ohtsuki and Ofuruton[8] have reported the generation of plasma fireballs formed by microwave interference in air. The frequency was 2.45 GHz, at power levels from 1 to 5 kW. These microwave-generated fireballs lasted several minutes at 1 atm and were reported to have lasted from 1 to 2 s after the microwave power was turned off. These microwave-generated atmospheric plasmas are hard to understand in terms of known dissociation processes in air, but the requirement for steady-state rf energy input makes the relevance of these experiments to ball lightning unclear.

CHARACTERISTICS OF BALL LIGHTNING

In this section we review the properties of ball lightning as revealed by a large database of observations documented in Refs. 1 through 6 and 9. We also summarize material that has been used elsewhere in a different context.[10]

Appearance of Ball Lightning

In ~80% of the cases, ball lightning is observed after a lightning stroke or in association with thunderstorm activity. There apparently are no observations of the *formation* of lightning balls, which is unfortunate because such observations might provide important clues to the physical mechanisms of the lightning balls' formation and structure. Usually, ball lightning is observed singly, but there are isolated reports of three or more lightning balls being observed simultaneously. Ball lightning is sometimes seen to sink relatively slowly through the atmosphere before striking the ground, but most frequently it appears to float, descending very slowly toward the ground or remains suspended at a constant distance above the ground. Ball lightning is usually observed to be spherical, hence its name, but isolated instances of oval or spindle shapes have also been reported.

There appear to be very few, if any, reports of structure within ball lightning, most observers reporting simply a luminous, featureless, spherical ball. Ball lightning has been observed to have a wide range of luminosity, from barely visible above ambient light levels to intensely and dazzlingly luminous. The colors reported have ranged across the entire visible spectrum, with some bright blue and others yellow, orange, or red in color. Observers are usually unaware of any sound being emitted by ball lightning, although most observations are made at a significant distance from it. Several observers have reported the sudden termination of ball lightning. Sometimes this occurs with no visible effects and is silent or has a barely audible popping sound. On other occasions, the disappearance of ball lightning is accompanied by a loud explosion.

Ball lightning has been observed to move against the prevailing wind, to follow electrical wires or electrical conductors, and sometimes to hover in one place for many seconds. A significant observation has been repeated independently by a number of observers and is very difficult to reconcile with many ball lightning models. Ball lightning has moved toward a glass window, disappeared on one side, reappeared on the other side, and then continued on its path moving away from the window. Related observations are the several occasions on which ball lightning has been observed moving down the aisle of a passenger airplane in flight after the plane had been struck by lightning.

Diameter of Ball Lightning

A distribution function of ball lightning diameter, in centimetres, is shown in Fig. 1, taken from Singer.[3] These data were provided by four surveys of large populations, each containing the number of cases indicated in the upper portion of the figure. These distributions start out with a very low frequency of occurrence at small diameters, rise through a maximum, and then decrease for large diameters. The fall-off of observations at small diameters is probably due to observer bias because small objects are less likely to be noticed than large ones, particularly as the distance between the observer and the ball lightning increases. These data indicate that the most probable diameters are somewhere between 15 and 50 cm, and diameters of a metre or more have been observed. Indeed, individual reports exist of ball lightning more than 2 m in diameter.

When the cumulative distribution function of these data is plotted as a function of the ball lightning diameter, an interesting lognormal relationship emerges. Figure 2, taken from Rayle,[6] shows that the cumulative distribution of ball lightning diameters observed in his and in the McNally surveys both have a lognormal distribution, with a median diameter of ~30 cm. The cumulative distribution of charge transferred by lightning strokes is also plotted in Fig. 2. This also obeys a lognormal distribution, but with a different slope, suggesting a different standard deviation and a different underlying physical mechanism. Here, the defects of observer bias apparently do not come into play until one gets below a diameter of 5 cm or so; at the high end, the data remain lognormal up to ball lightning diameters of ~1.5 m.

Ball Lightning Lifetime

The questionnaire distributed in connection with the major ball lightning surveys discussed in Refs. 3 and 4 attempted to establish a lifetime for the ball lightning. These lifetime data were very likely to have been subject to observer bias because ball lightning that existed for a few seconds or less hardly allowed time to identify the phenomenon as ball lightning and was probably less likely to come to the attention of an observer in any case. In addition, most observers were frightened by the ball lightning, and this disturbed their normal ability to estimate elasped time accurately and, in many cases, caused them to leave the scene before the ball lightning disappeared. On the ordinate of Fig. 3, taken from Rayle,[6] is plotted the cumulative distribution function of reports of ball lightning durations less than a given duration T, and on the abscissa is plotted the duration of the ball lightning in seconds. Data from

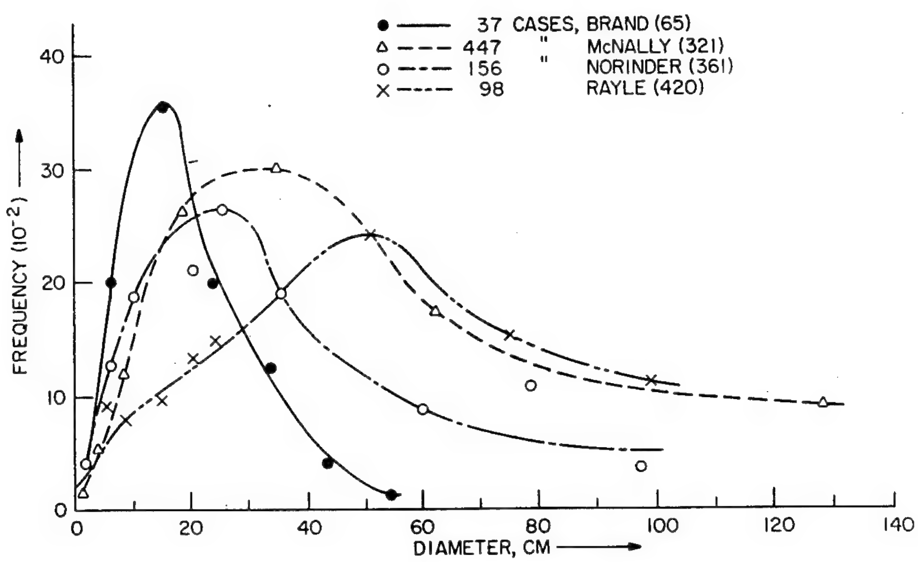


Fig. 1. Distribution function of ball lightning diameters from four surveys, incorporating the number of reported observations shown at the top of the figure. (Taken from Singer.[3])

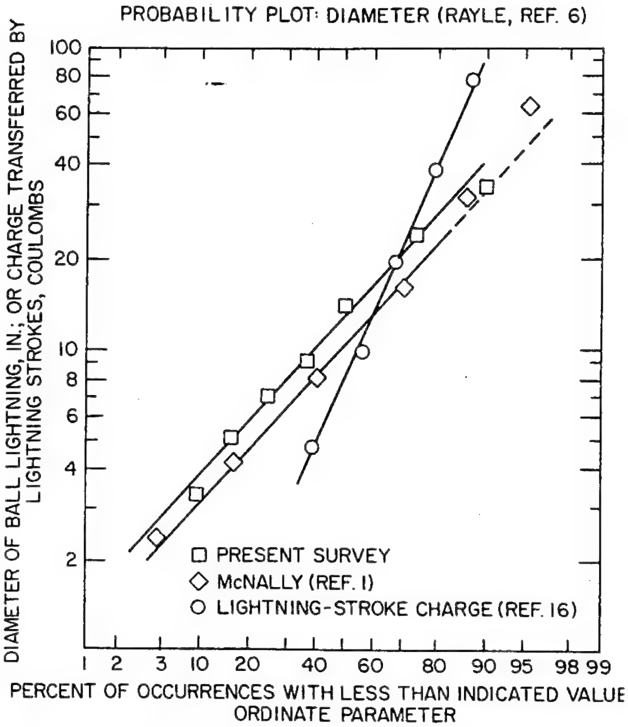


Fig. 2. Cumulative distribution of ball lightning diameters from two surveys (squares and diamonds) and the charge transferred by lightning strokes (circles). (Taken from Rayle.[6])

both the McNally[5] and Rayle[6] database are plotted. The median duration, 0.5 on the ordinate, is ~3 to 5 s; in both surveys a few durations in excess of 36 s were observed. Some ball lightning has been observed to last for several minutes. These relatively long lifetimes (by fusion confinement standards) are one of the most intriguing features of ball lightning and have motivated several of the surveys, including those in Refs. 5 and 6.

Ball Lightning Energy Content

The database of ball lightning observations has been carefully worked over in an attempt to determine the energy content of ball lightning. In some cases, observers reported information on effects or damage resulting from the final disappearance or explosion of ball lightning. In a few cases, trained observers, including military munitions experts, were able to observe this damage firsthand after the event and to make more refined estimates of the amount of energy required to produce the observed damage. Such investigations are described by Singer[3] and Barry.[4] These investigations have shown that ball lightning may have a total energy content ranging from 0.01 J to values >10 MJ. The energy content of a hand grenade is ~1 MJ, for comparison. A characteristic value for the energy content of ball lightning is ~10 to 100 J. This energy content is dangerous because it takes only ~1 J of electrical energy to kill a human being. Indeed, there are several reports in the literature of individuals being injured or killed by ball lightning, including the classic case of Richmann.

Ball Lightning Energy Density

In ~13 cases discussed by Barry,[4] enough information was available to estimate not only the energy content of the ball lightning but also its energy density. A

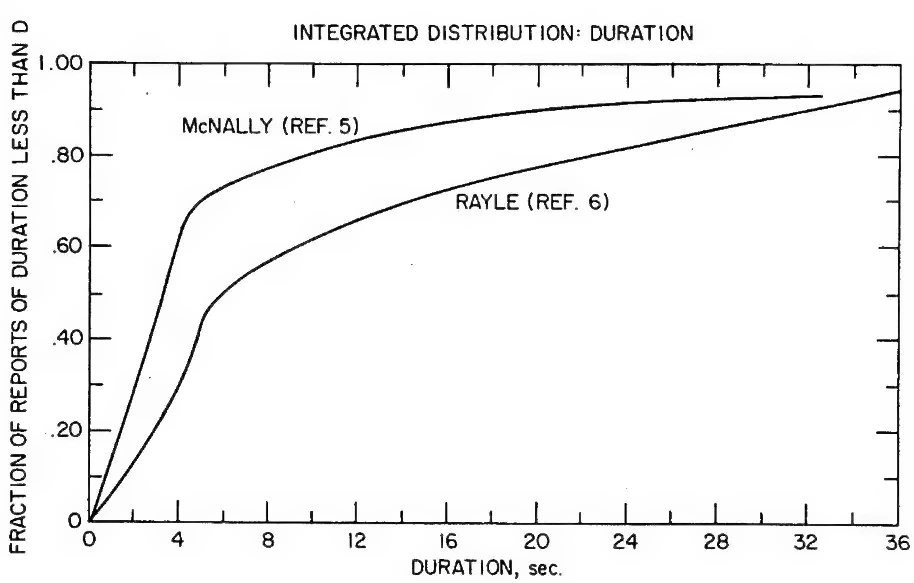


Fig. 3. Cumulative distribution function of reported ball lightning durations from the McNally[5] and the Rayle[6] surveys. (Taken from Ref. 6.)

lognormal cumulative probability distribution for these data is plotted in Fig. 4, from Barry.[4] These data fall along a straight line, indicating a lognormal distribution, with a median energy density of ~5 J/cm^3 and extreme values ranging from $<10^{-3}$ J/cm^3 to values higher than 10^5 J/cm^3.

The very high value of the energy density at the upper end of the distribution is significant, both in its implications for fusion and military applications and as a constraint on possible models for ball lightning. For example, fully ionized and dissociated atmospheric air would have an energy content of ~170 J/cm^3, far below the upper range of the data shown. The more energetic forms of ball lightning are therefore inconsistent with a model based on a ball of ionized plasma that recombines during the lifetime of the ball lightning. Energy densities in excess of 10^4 J/cm^3 also appear to rule out a chemical origin for the more energetic forms of ball lightning. For example, the energy density of TNT, which has one of the highest energy contents of any solid explosive, is ~2000 J/cm^3, far below the maximum observed for ball lightning. Almost the only energy storage mechanism for energy densities >1000 J/cm^3 is stored magnetic energy, probably an important clue to the physics of ball lightning.

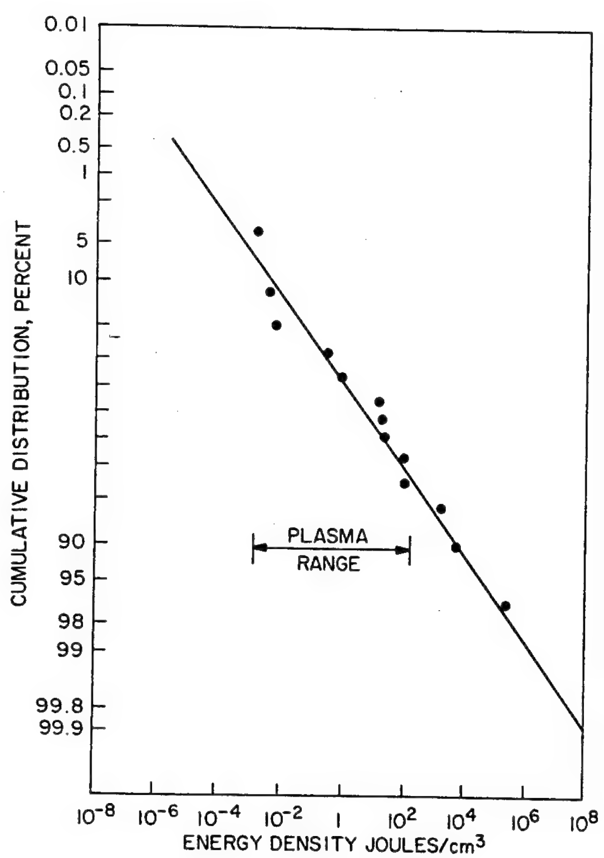


Fig. 4. Lognormal cumulative distribution of the energy density of ball lightning. (Taken from Barry.[4])

Ball Lightning Mass Density

The mass density of ball lightning can be estimated from the fact that it usually appears to float above the surface of the earth at a constant height as though it were a bubble of hot gas with neutral buoyancy. This characteristic suggests that the mass density of ball lightning is close to that of atmospheric air, $\sim 1.3 \times 10^{-3}$ g/cm^3.

Ball Lightning Kinetic Pressure

Ball lightning is observed to maintain an approximately constant diameter during its entire lifetime, thus suggesting a balance between the external atmospheric pressure and the net kinetic pressure of the plasma/magnetic field configuration inside the ball lightning. Because the external pressure on ball lightning is 1 atm, this places an upper bound on the net kinetic pressure inside the ball lightning of no more than 10^5 N/m^2.

The aforementioned characteristics of ball lightning are summarized in Table I. The low and high values reported in this table are near the extreme wings of the observed distribution of properties; the characteristic values are the most probable or median values reported in the literature, such as in Refs. 2 through 6.

BALL LIGHTNING MODELS

The intriguing characteristics of ball lightning have elicited a wide variety of proposed models to explain the phenomenon. Here we divide ball lightning models into three principal groups: the older models of ball lightning formation, which are discussed in the books by Singer[3] and Barry[4]; fusion-related models, in which ball lightning has been identified with one or more successful magnetic containment configurations used in fusion research; and finally, the Koloc model, put forward by Paul M. Koloc, which seems best to incorporate extensive ball lightning observations with physical processes familiar as part of the worldwide magnetic fusion program.

Older Ball Lightning Models

In this section we discuss some ball lightning models from the older literature on the subject.

Psychogenic Models

It is sometimes suggested, even in recent times, that ball lightning has no physical existence and is psychogenic in origin, being the result of after-images of lightning strokes, reflections, optical illusions, hallucinations, or mass hysteria. This school of thought puts ball lightning in a class with aliens from outer space descending from unidentified flying objects and with the appearance of religious icons in the sky. The current consensus of ball lightning investigators is that these

TABLE I

Properties of Ball Lightning

Property	Low Value	Characteristic Value	High Value
Diameter (cm)	1	10 to 15	150
Duration (s)	1	3 to 6	100
Energy content (J)	0.01	10 to 100	10^7
Energy density (J/cm^3)	10^{-3}	5	10^5
Mass density (g/cm^3)	1.0×10^{-3}	1.3×10^{-3}	1.5×10^{-3}
Kinetic pressure (N/m^2)	1×10^5	1.016×10^5	1.1×10^5

psychogenic explanations are inconsistent with a large body of observations, including many cases in which several observers saw the same phenomenon. Another factor inspiring confidence in the observations is the lognormal distribution functions that have emerged from large numbers of reported observations, such as those in Figs. 2 and 4. It may be particularly significant that the lognormal distribution for ball lightning diameter in Fig. 2 was observed at two different sites, at different times, in different parts of the United States and that the same type of lognormal distribution function is also known to describe the physics of the total charge contained in lightning strokes.

Chemical Models

Chemical models for ball lightning are still taken very seriously, particularly in Japan.[9] In these models, ball lightning is explained as the result of chemical reactions in the atmosphere, the origin of which might be chemically active species generated by a lightning stroke or the ignition of gaseous fuels such as swamp gas or methane by atmospheric electricity. The chemical model is consistent with the significant minority of ball lightning observations that have been made in the absence of thunderstorms or lightning strokes and the relatively low energy density of many examples of ball lightning, which can be explained by the energy provided by chemical reactions. However, the chemical model is inconsistent with a significant number of observations of extreme damage done by ball lightning and the high energy densities at the upper end of the range shown in Fig. 4. The chemical model of ball lightning has enough currency that some ball lightning investigators suggest that ball lightning may consist of two different types, one having a chemical origin and the other not.

The rf Energy Models

A third model for ball lightning formation originated in Russia and is sometimes called the Kapitza model after its originator, the physicist Peter Kapitza. This model sees ball lightning as an atmospheric plasma generated by intense rf power created by lightning strokes or atmospheric electricity. Indeed, the rf experiments of Powell and Finkelstein (see Ref. 4) and the similar experiments of Ohtsuki and Ofuruton[8] have generated self-luminous plasma balls that resemble ball lightning in many respects. This rf-generated "ball lightning," however, requires a large continuous input of rf power, and such steady-state sources of rf energy are known to be inconsistent with the natural phenomenon, where rf interference, for example, is rarely observed in association with ball lightning.

The Vortex Plasmoid

Finally, a model based on a self-contained magnetically confined plasma, the "vortex plasmoid," has been discussed by Singer[3] and is illustrated in Fig. 5, taken from Ref. 3. This model sees ball lightning as a luminous, self-contained toroidal plasma configuration having a large toroidal current ring, the magnetic field of

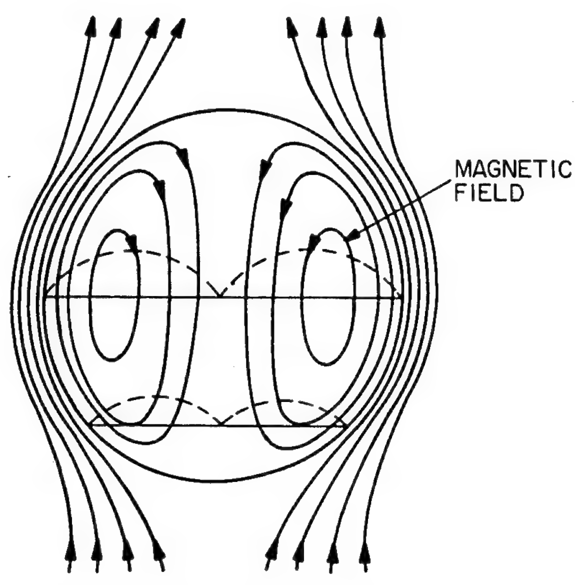


Fig. 5. The vortex plasmoid model for ball lightning. (Taken from Singer.[3])

which interacts with the earth's magnetic field. One difficulty with this model is that the observed motion of ball lightning appears to be independent of the local direction of the earth's magnetic field at the point of observation. This model has inspired more recent attempts, such as that of Witalis,[11] to understand the physics of ball lightning.

Fusion-Related Ball Lightning Models

Ball lightning differs from the plasmas used in magnetic fusion research in several significant ways. There is no analog in fusion research to the existence of a confined plasma at 1 atm. Fusion experiments start out at a moderately good vacuum and operate at pressures well below 1 Torr. In fusion experiments, variation of the surrounding neutral background gas pressure has little effect on the equilibrium or stability of the plasma, beyond the possible introduction of impurities. Also in fusion research, there is no analog to the free-floating plasma bubble that is the characteristic feature of ball lightning. All magnetic fusion experiments at present are tied down to external confining magnetic field coils, even though in some fusion confinement configurations, such magnetic fields play a relatively minor role in confining the plasma.

Several dozen alternate magnetic containment configurations have been discussed in Ref. 12, and a few of these have characteristics that tempt one to draw an analogy to ball lightning, even though the most similar of the known magnetic containment configurations differ from ball lightning in the ways described in the previous paragraph. First is the Astron, or field-reversed mirror, illustrated in Fig. 6, in which a torus of plasma containing a large axisymmetric circulating current is confined in the midplane of a magnetic mirror geometry. The plasma current flows in a sense opposite to that in the coils that generate the mirror magnetic field, thereby generating a diamagnetic field, reducing the magnetic field on the axis. If one eliminated the external field coils and allowed the torus of plasma to form an insulating blanket against the surrounding neutral gas, the result would look very similar to ball lightning. A field-reversed, highly diamagnetic ring of plasma that can be moved from place to place and manipulated by guiding magnetic fields has been described recently by Sudan.[13]

A similar fusion-related magnetic confinement geometry that resembles ball lightning is generated by the field-reversed theta pinch,[12] which is illustrated in Fig. 7. In this configuration, an elongated torus of plasma with large diamagnetic currents is confined by a magnetic mirror field generated by a theta pinch. The plasma configuration and magnetic field geometry look very similar to that of the field-reversed mirror, although they are arrived at by very different means. The field-reversed theta pinch relies on transient means of plasma production and is transient itself.[14]

Finally, the spheromak configuration[12] illustrated in Fig. 8 probably resembles ball lightning more closely than any other fusion-related magnetic containment configuration, partly because of its efficient confinement by the self-generated magnetic field produced by currents inside the toroidal plasma and partly because of the relatively weak external magnetic field necessary to stably restrain the spheromak plasma. The spheromaks also have a "separatrix," which separates the externally produced magnetic field from that generated by the current flowing in the toroidal plasma. The site of this separatrix would be a natural place to expect a gas blanket or mantle to form if it were surrounded by dense neutral gas. Some interesting experimental observations on the current profiles and other characteristics of a spheromak plasma have been reported by Al-Karkhy et al.,[15] and these provide a database with which eventual measurements on ball lightning might be compared. Some theoretical aspects of self-confined plasmas from a magnetohydrodynamic (MHD) point of view have been reported by Witalis.[16]

All three of the aforementioned fusion-related magnetic containment geometries are similar, consisting of a toroidal plasma with a large current strong enough to generate a poloidal magnetic field that keeps the plasma contained. They all possess a separatrix and require external magnetic field coils, the strength of which differs from one configuration to the next, to provide plasma equilibrium. In ball lightning, the pressure of the surrounding atmosphere may take the place of the magnetic pressure provided by the external magnetic field required to stabilize these geometries. The theory of these three magnetic containment configurations will probably form a useful basis for understanding the

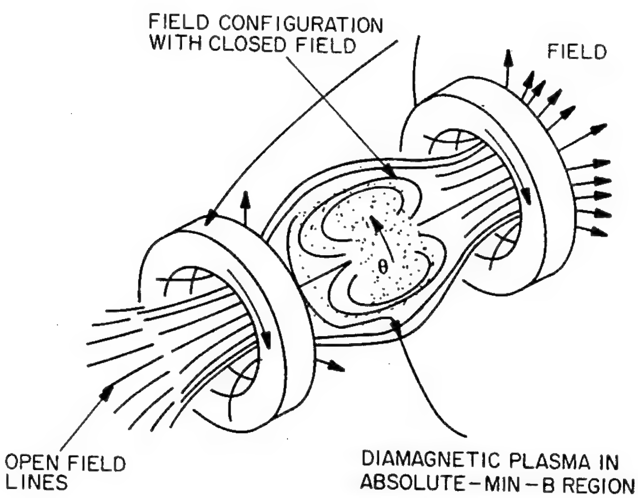


Fig. 6. A compact torus generated in an axisymmetric magnetic mirror. A high-beta, diamagnetic plasma that reverses the magnetic field is formed in the midplane, on the axis, and forms a region of minimum magnetic field. (Taken from Roth.[12])

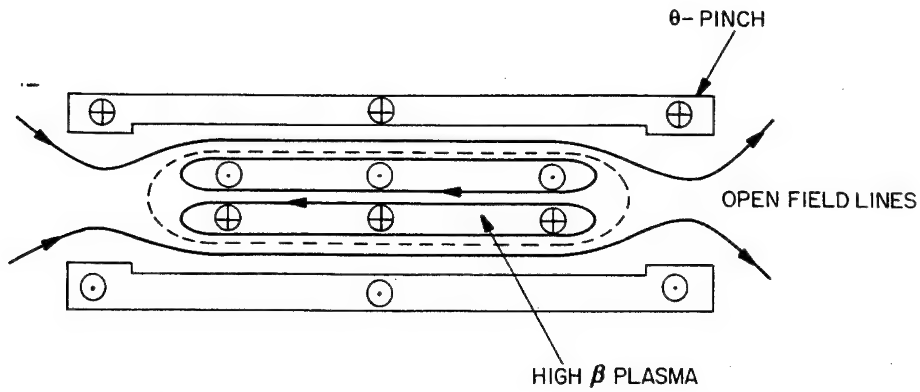


Fig. 7. The field-reversed theta pinch. (Taken from Roth.[12])

physical processes in ball lightning, especially the fundamental work of Witalis.[11,16]

THE KOLOC MODEL FOR BALL LIGHTNING FORMATION

A model for ball lightning formation was recently developed by Koloc.[17,18] Koloc's model is considerably more detailed than the older models, is better grounded in advances recently made in fusion research, and describes in detail the formation process as well as the ultimate ball lightning product. This model has resulted in a U.S. patent.[19]

According to the Koloc model, the physical processes that produce ball lightning begin with a lightning stroke, and end with ball lightning, after proceeding through the following series of sequential steps:

1. the Z-pinch
2. Bennett pinch equilibrium
3. the kink instability
4. nonlinear growth of the kink instability
5. torus formation
6. the sausage instability
7. mantle formation.

In this model, the first step in the formation of ball lightning is the creation of a linear Z-pinch by the ionized channel associated with an ordinary lightning stroke, illustrated in Fig. 9. The large currents in the plasma channel squeeze the plasma because of the azimuthal field generated by the high axial current flowing

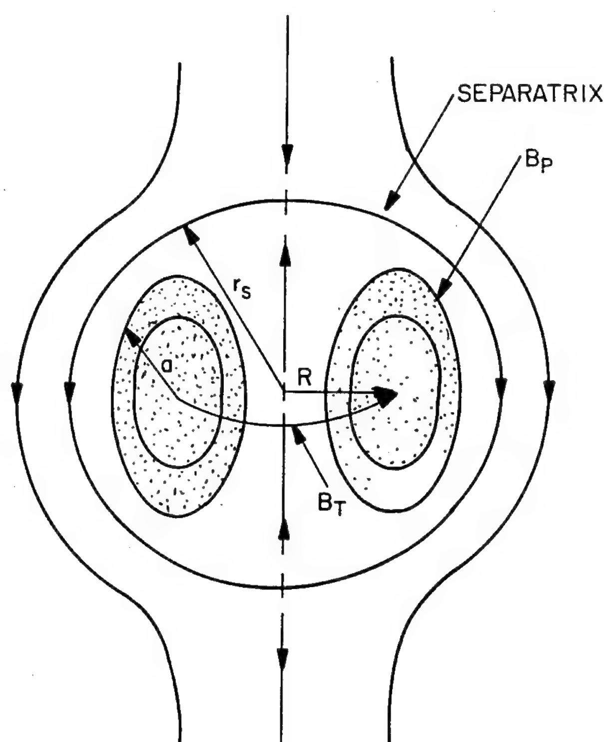


Fig. 8. The spheromak configuration. A weak vertical magnetic field stabilizes a toroidal current-carrying plasma. (Taken from Roth.[12])

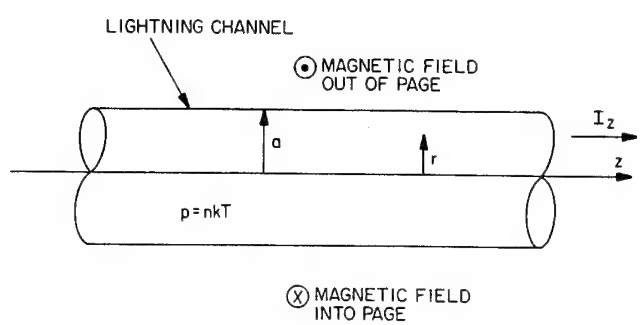


Fig. 9. A cylindrical current-carrying plasma corresponding to a lightning channel in Bennett pinch equilibrium. (Taken from Roth.[12])

in the lightning stroke. The plasma forms a Bennett-pinchlike equilibrium[12] between the outward kinetic pressure of the plasma and the inward force of the poloidal field. This balance is unstable and will lead to the growth of kink and sausage instabilities. In the kink instability, illustrated in Fig. 10, the initially axisymmetric cylindrical channel will tend to bend into a helical spiral, which looks much like a single strand of a multistrand rope. It is this stage of the Koloc model that may have been observed in the high-voltage sparks reported in Ref. 7. This unstable equilibrium worsens because the poloidal magnetic field is stronger on the inside of the curved plasma than it is on the outside.

The Koloc model develops as the kink instability grows in a nonlinear manner, resulting in an extreme distortion of the cylindrical channel into a series of helical turns that look like a helical spring, as illustrated in Fig. 11. The current in adjacent turns of the coil illustrated in Fig. 11 flows in the same direction, and these tend to attract each other, leading to collapse and the formation of a single torus in the manner indicated in Fig. 12. The result is a torus of plasma with a circulating current greater than that in the original lightning channel by a factor equal to the number of turns in the helix that formed it. After the torus forms, the main lightning channel can be pinched off by the sausage, or pinch, instability[12] illustrated in Fig. 13. In the sausage instability, a small perturbation in the diameter of the plasma leads to a change in the current density and a corresponding change in the azimuthal magnetic field. A small constriction tends to grow as the current density and azimuthal magnetic field increase, and this instability can lead to the pinching off of the plasma channel above and below the torus, as shown in Fig. 12.

Thus far, the Koloc model depends on well-understood plasma phenomena that have been repeatedly observed in the laboratory. However, if a bare torus of highly ionized plasma were to exist in the atmosphere without some form of shielding from neutral atmospheric gases, the electron-neutral scattering and energy dissipation would quench the plasma on a time scale measured in milliseconds. To deal with this objection, the Koloc model assumes that the torus of Fig. 12 forms a thin shell of very hot electrons, as indicated schematically in Figs. 12 and 14, which insulates the plasma torus from the surrounding neutral gas. This thin layer is called the mantle in the Koloc model. These hot electrons are maintained by currents flowing along lines of longitude from one pole of the dipole to the other that heat the electrons in the thin shell to relativistic energies high enough to have scattering cross sections consistent with the long lifetimes observed in ball lightning. The energy required to maintain this thin shell of relativistic electrons is supplied by the slow collapse of the dipolar magnetic field and by the stored magnetic energy in the circulating current of the torus.

The outcome of these processes is a torus of plasma containing a large circulating current that generates a dipolar magnetic field confined within a shell of hot electrons. Immediately outside the hot electron boundary is a partially ionized gas that fades off into the surrounding neutral atmosphere. In the Koloc model, illustrated in Fig. 14, ball lightning is thought of as a plasma bubble with number densities lower than that of the atmosphere surrounding it but with kinetic temperatures and magnetic pressures that provide an expansionary force to keep the plasma bubble inflated against the pressure of the surrounding atmosphere.

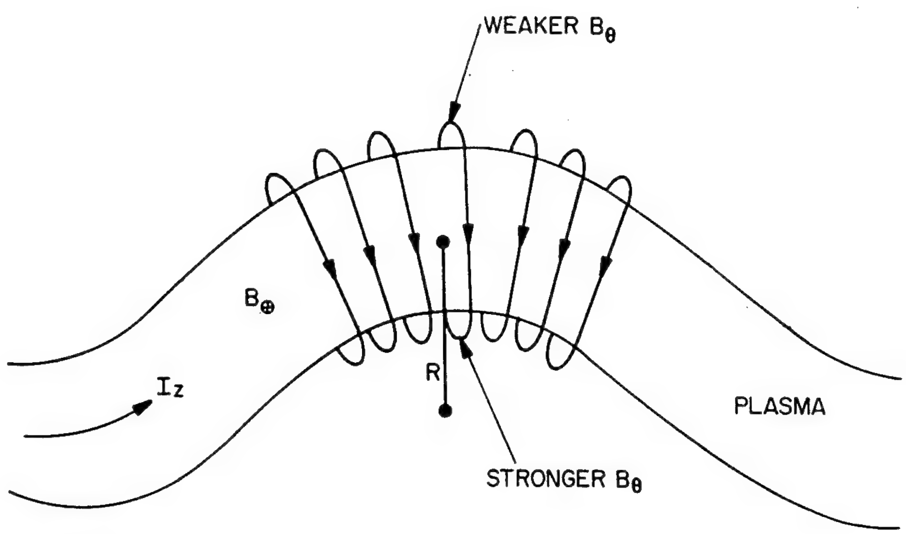


Fig. 10. Development of the kink instability in the lightning channel of Fig. 9. The helically twisted plasma looks like a single strand of multistrand rope, and the instability is driven by the stronger magnetic field on the inside radius of curvature. (Taken from Roth.[12])

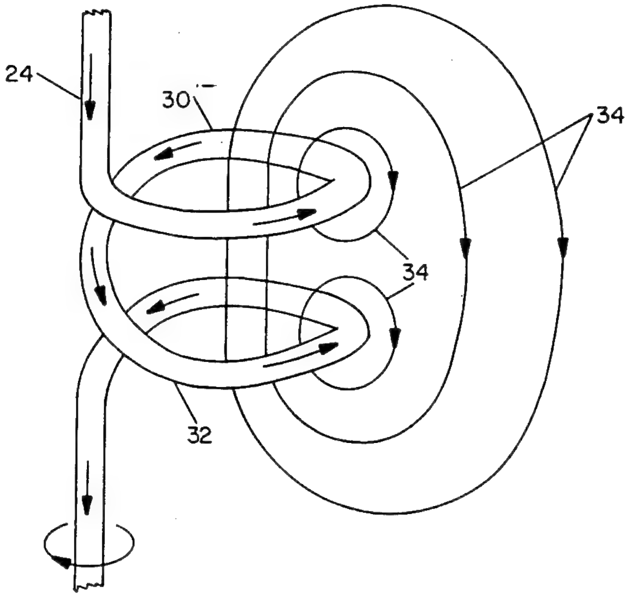


Fig. 11. Nonlinear evolution of the kink instability prior to torus formation. (Illustration from Koloc.[19])

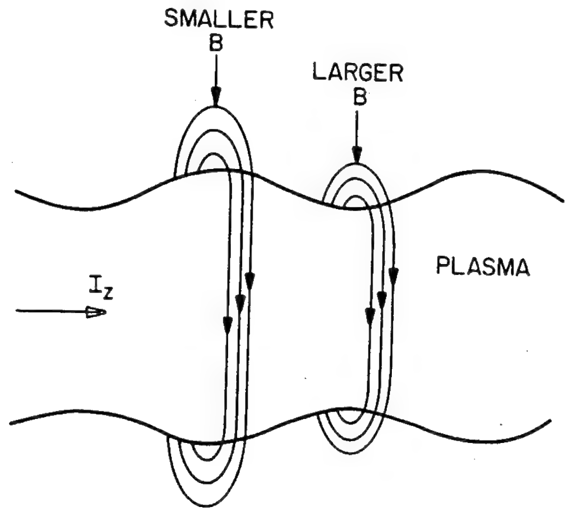


Fig. 13. Development of the sausage or pinch instability due to axial perturbations in the plasma column diameter. Such perturbations can cut the plasma torus off from the main lightning stroke after the torus formation shown in Fig. 11. (Taken from Roth.[12])

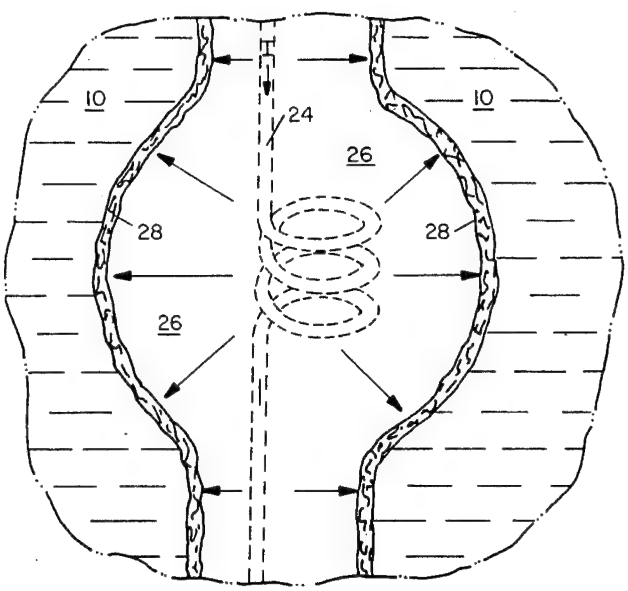


Fig. 12. Torus formation in the Koloc model. (Taken from Koloc.[19])

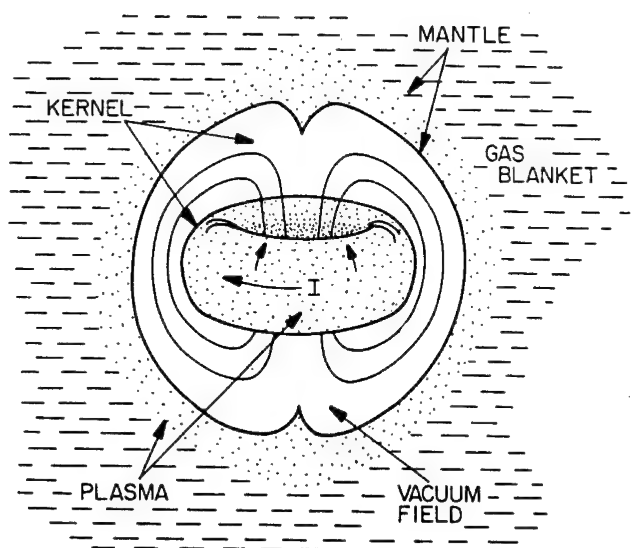


Fig. 14. The end point of the Koloc model, showing a toroidal plasma insulated from the surrounding neutral gas by a high-energy electron shell. The "kernel" forms a plasmalike bubble, which is maintained by a combination of magnetic and plasma pressure against the pressure of the surrounding atmosphere.

Detailed models have been developed by Koloc for the hot electron boundary and for the physical processes in the mantle that allow ball lightning to maintain itself in the atmosphere for long periods of time.[17,18]

The magnetic containment configuration described by the Koloc model is very similar to that of the Spheromak and the Field-Reversed Mirror, or Astron, except that it does not require an external magnetic field for confinement. The ultimate confinement mechanism in the case of ball lightning would be the surrounding neutral atmosphere. If the Koloc model is correct, the ball

lightning plasma could be compressed or rarefied by increasing or decreasing the pressure of the surrounding neutral gas. A similar magnetic mechanism for high-current diamagnetic ion rings has been suggested by Sudan.[13]

The requirement for a relativistic shell of electrons surrounding the plasma torus is probably the least satisfactory aspect of the Koloc model and the one that thus far has no precedent in laboratory plasma physics. The presence of significant numbers of relativistic electrons as an essential feature of a ball lightning model would seem to be inconsistent with the very low energy content implied by some ball lightning observations. This aspect of the Koloc model was formulated to deal with the very long lifetime that ball lightning is observed to have in atmospheric air.

A mechanism other than relativistic energies by which the electrons could have a very long confinement time and low scattering cross section is electron scattering in a Ramsauer gas. The Ramsauer gases are those gases that, because of quantum mechanical effects, have very low electron-neutral scattering cross sections at low electron energies. Figure 15 shows electron-neutral scattering cross sections for several gases taken from Ref. 20. Of the gases shown, argon is a Ramsauer gas, with an electron-neutral scattering cross section far lower than that of other common gases. Until recently, there was no reason to think that ball lightning could reasonably contain a Ramsauer gas and thus have a long electron-neutral scattering time. It has become known,[11] however, that some nitrogen oxides are Ramsauer gases. It is possible that during the intense plasma chemistry associated with a lightning stroke, the oxygen and nitrogen of the atmosphere may combine to form nitrogen oxides, which may be Ramsauer gases. These Ramsauer gases may then permit the electron population to remain energetic for far longer than would be the case if the electrons were to scatter against ordinary oxygen or nitrogen molecules.

IMPLICATIONS OF BALL LIGHTNING OBSERVATIONS

The large body of ball lightning observations indicate very strongly that it is a real phenomenon, the physics of which should be explainable in terms of known physical processes. If we are willing to grant the reality of ball lightning, then what are the implications

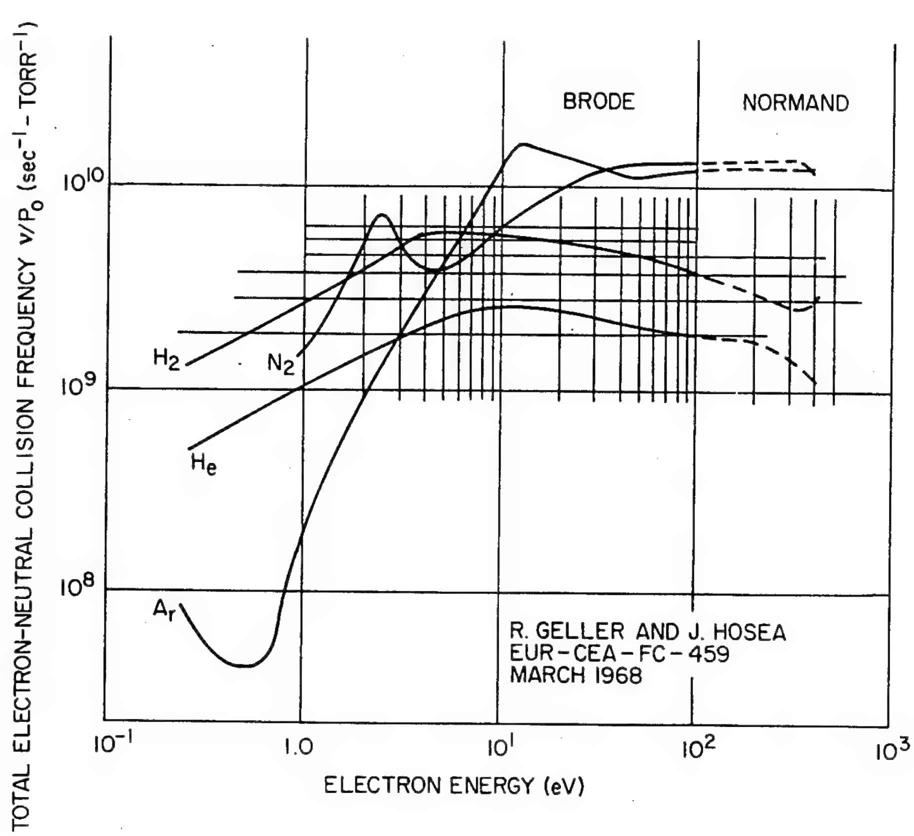


Fig. 15. Total electron-neutral collision frequencies for four gases, from Ref. 20, showing the Ramsauer minimum for argon gas.

of interest to the plasma research community? One feature of ball lightning that motivated several of the surveys cited previously[5,6] is the long duration of ball lightning, ranging from ≈ 1 s, up to >130 s. These times are much longer than the containment time required for a net power-producing fusion plasma, and so the existence of ball lightning suggests a plasma confinement method that may be of fusion relevance, if only because of its ability to confine plasma for periods of time far longer than those required for fusion applications. The physical processes responsible for the long lifetime of ball lightning may be of interest in fusion research for the additional reason that it might tell us with what gases we might surround the fusion plasma to minimize charge exchange and electron-neutral scattering losses.

Another feature of ball lightning observations is the large energy density and energy content associated with some ball lightning observations. Energy densities of $>10^4$ J/cm^3 indicate a magnetic energy storage mechanism in ball lightning, and total energies up to 10 MJ indicate plasmas energetic enough to be of fusion relevance. The magnetic containment method responsible for ball lightning would be of interest to fusion research because of the MHD stability of ball lightning over many tens of seconds.

In addition to suggesting that there are new and previously unknown physical mechanisms for the magnetic containment of plasmas and the long-duration stable confinement of plasma in atmospheric air, ball lightning has potential applications in at least three areas in which the plasma research community has been active. These potential areas of application include ball lightning as a military weapon, potential fusion applications of ball lightning, and the implications of ball lightning for industrial plasma processing at 1 atm.

BALL LIGHTNING AS A MILITARY WEAPON

Suppose it were possible to generate ball lightning with an apparatus that was small and light enough to be mobile but not small enough to be portable, like small arms. To do much damage, a lightning ball would have to store at least 1 MJ of energy, and a capacitor bank large enough to store this energy would be too large to be easily portable.

Effects on Troops

Perhaps the most significant effect of ball lightning on troops might be psychological. If no simple countermeasures to ball lightning could be developed, the sight of a lightning ball approaching an individual would probably inspire fear and panic and cause very significant distraction. The ball lightning literature contains many reports of individuals who were stunned by ball lightning and a few, like Richmann, who died from contact with ball lightning. It is not clear whether this spectrum of effects on humans is the result of a range of stored energy or some other factor associated with ball lightning, but it is moderately clear that if ball lightning could be formed at will, it should be possible to achieve an effect on humans that ranges from stunning to death.

Ball lightning would have a number of advantages over kinetic weapons based on ordinary firearms because the operator of a ball lightning projector should be able to adjust the ball lightning to achieve a spectrum of effects ranging from brief stunning to death. A ball lightning weapon could therefore be used in police work at a setting that was known not to be fatal or adjusted for lethal effect when used in warfare. Another potential advantage of ball lightning over kinetic weapons is that there appear to be no reports of ball lightning stunning people and then leaving them maimed. Thus, ball lightning would probably disable troops without permanently injuring or maiming them, one of the ancient disadvantages of kinetic weapons.

Effects on Equipment

For reasons that were previously outlined, including the observation of very high energy densities, ball lightning appears to be energized by stored magnetic energy, which in natural ball lightning can reach levels of at least 10 MJ. The lightning balls can be thought of as a form of portable electromagnetic pulse. If a lightning ball were to come into contact with antennas or any solid-state electronic system, the high voltages and high currents associated with sudden decay of the stored magnetic energy would probably damage or destroy any electromagnetic receiver. A ball lightning projector could probably irreversibly damage most sophisticated weapons used on the modern battlefield that contain solid-state electronic components.

It is also likely that, if ball lightning can be accurately aimed, it should be possible to trigger munitions with the sudden and rapid decay of its stored magnetic energy and to effect other forms of physical destruction. The literature on ball lightning contains numerous descriptions of severe damage done by the explosion of a lightning ball. In a few cases, explosives experts have identified the energy content of the source as being >10 MJ. Many cases of the demolition of large trees or substantial masonry structures have been reported. These observations indicate that ball lightning should have a substantial capacity for physical destruction, but the potential drawback of this is that the capacitor banks that would be needed to supply such a ball lightning projector are relatively heavy and cumbersome at the level of multimegajoules of stored energy.

APPLICATION OF BALL LIGHTNING TO FUSION REACTORS

Suppose that it became possible to generate ball lightning in the laboratory and that the plasma parameters of ball lightning could be made to include the

densities, kinetic temperatures, and containment times required to meet the Lawson criterion. As a stimulus to ball lightning research for fusion applications, it is useful to consider the fusion-relevant characteristics of ball lightning and the potential advantages of ball lightning fusion reactors.

Fusion-Relevant Characteristics of Ball Lightning

Some of the fusion-relevant characteristics of ball lightning are listed in Table II. In the first column are listed characteristics that are relevant to fusion applications and on which information is available from the existing ball lightning database. In the second column is the range of parameters from the available ball lightning observations for the characteristics in the first column, and in the third column are shown the approximate requirements for a net power-producing, self-sustaining deuterium-tritium (D-T) fusion reactor. It is evident that the duration of ball lightning is longer than the particle containment time needed for a net power-producing fusion reactor.

The second row of Table II indicates that the energy density of ball lightning can be far higher than the 1 J/cm^3 characteristic of a self-sustaining D-T fusion reaction. The third line of Table II indicates that ball lightning can be large enough to provide significant amounts of fusion power if fusion energy densities of 1 to 10 MW/m^3 could be maintained in a ball lightning fusion reactor. The fourth row indicates that the kinetic pressure of ball lightning, ~1 atm, is comparable to the kinetic pressure $p = nkT$ of a magnetic fusion reactor, which would range from 1.6 to 10 atm for D-T and advanced fuels, respectively.

The ion and electron number density in ball lightning is very poorly known and would have to be somewhere below 2.7×10^{19} particle/cm^3, the particle number density of the neutral atmosphere. In a net power-producing D-T fusion reactor, an ion number density of $\sim 10^{14}/cm^3$ would be required, and advanced fuel reactors would require densities of perhaps two or three times this value.[12] Finally, in the last line of Table II the kinetic temperature of ball lightning is very poorly known but must be more than the temperature of atmospheric air. For a self-sustaining D-T fusion reactor, the kinetic temperature of the ions must be ~10 keV, with values of three to five times this value required to burn advanced fuels.

TABLE II

Fusion-Relevant Characteristics of Ball Lightning

Characteristics	Ball Lightning Observations	Self-Sustaining D-T Fusion Requirements
Duration (s)	1 to >100	1 to 10
Energy density (J/cm^3)	10^{-3} to 10^5	1
Diameter	~1 cm to 2 m	>1 m
Kinetic pressure (atm)	~1	1.6 to 10
Number density (cm^{-3})	Poorly known	$\sim 10^{14}$
Kinetic temperature (eV)	Poorly known, >0.025	10^4

Potential Advantages of Ball Lightning Reactors

The first potential advantages of ball lightning reactors might be small size and power output. Existing studies of D-T tokamak fusion power plants[12] suggest that such reactors must produce several gigawatts of thermal power and be so costly and large that they cannot be used for anything other than central station electric utility power plants. The observed size of ball lightning is an encouraging indication that a fusion reactor based on ball lightning might be small enough to be used in mobile applications and of small enough power output that applications of considerably smaller scale than electric utility power plants could be considered.

The ability of ball lightning to exist in stable equilibrium at 1 atm suggests that, if desired, a ball lightning fusion reactor could be operated at 1 atm, like ordinary fossil fuel boilers, or at least without the necessity of an expensive vacuum system. This also implies that a knowledge of the physical processes that allow ball lightning to exist at 1 atm might have implications for the selection of the gas that should surround a fusion plasma to minimize charge exchange or scattering losses. On a more speculative note, the capability of ball lightning to operate at 1 atm also suggests that more exotic applications of ball lightning fusion power plants, such as rocket engines for earth takeoff or fusion-powered turbojets, may be possible.

The fact that nature produces ball lightning without costly or complicated equipment is an encouraging indication that once we understand how ball lightning is formed, the equipment needed to produce a ball lightning fusion plasma will itself be simple and require only relatively simple containment equipment by current standards of magnetic fusion research.

Another potential advantage of ball lightning fusion reactors is that the balance between the external atmospheric pressure and the kinetic pressure of the plasma should allow the plasma number density, temperature, and fusion power output to be controlled by compression or expansion of the neutral gas surrounding the ball lightning plasma. If one compresses the surrounding neutral gas, it is reasonable to expect that an adiabatic compression of the confining magnetic field and its associated plasma will occur, leading to a hotter, denser plasma and greater power output. Thus, while the ball of plasma is undergoing fusion reactions, the power output should be capable of being adjusted on demand. This type of reaction control was contemplated by Koloc in his U.S. patent.[19]

Finally, the ball lightning literature contains reports of ball lightning that lasted for durations of well over 100 s. There apparently is a slight tendency for small ball lightning to last for somewhat shorter times than large-diameter ball lightning, but on the basis of existing observations, it seems reasonable to expect that ball lightning reactor plasmas, once formed, should last at least 10 to 100 Lawson containment times and allow a virtually complete fusion burn without refueling. It is not possible to say at this time whether a refueling mechanism could be found that would allow the magnetic field in a ball lightning reactor to regenerate itself and maintain the plasma in the steady state; most likely, a ball lightning fusion reactor will be a repetitively pulsed device, similar to that suggested by Koloc.[19]

Ball Lightning Fusion Reactor Concepts

The potentially small size and ability of a ball lightning fusion reactor to operate in the atmosphere open up a large variety of potential applications that are not possible for most other magnetic fusion containment concepts because of their unavoidably large size.[12] Such potential applications include space power and propulsion systems, where power outputs ranging from 100 kW to 200 MW are required, a range not easily supplied by the D-T tokamak or other mainline magnetic fusion concepts. The possibility of a ball lightning fusion reactor operating in the atmosphere may open up, for the first time, a realistic possibility of a fusion rocket capable of operating from the surface of the earth to low earth orbit. Prior to the emergence of this concept, fusion power and propulsion systems for space applications were restricted to the vacuum of outer space.

The potentially small size and simplicity of ball lightning generation and confinement equipment would open up a wide range of mobile applications of fusion reactors for land, sea, and air transportation. It is intriguing that ball lightning as small as 1 or 2 cm in diameter has been observed. If something this small were capable of fusion reactions, fusion engines for automobiles, trains, and trucks would not be out of the question. Even if a ball lightning fusion power plant required plasmas with dimensions of several metres, applications to submarines and surface ships might be possible. The capability of ball lightning to operate in the atmosphere raises the possibility of a fusion energy source for aircraft, with a turbojet engine or fanjet engine using fusion rather than chemical fuel in the combustor. Another application that could follow from the potentially small size and simplicity of a ball lightning fusion reactor is that distributed household primary energy sources might be possible in which every individual household and apartment building has its own fusion reactor to provide heating, air conditioning, water purification, and electrical power.

IMPLICATIONS OF BALL LIGHTNING FOR INDUSTRIAL PLASMA PROCESSING

In the field of industrial plasma engineering, nearly all industrial plasma processing except that done with thermal plasmas is accomplished at low pressures inside elaborate and expensive vacuum systems. The cost of vacuum systems and the energy cost of vacuum pumping tend to dominate the cost of nearly all products made below atmospheric pressure by industrial plasma processing methods. From the preceding discussion, it is reasonably clear that one implication of the existence of ball lightning is that steady-state, low-power glow discharges in atmospheric air should be possible. These glow discharges probably would involve a Ramsauer-effect gas, such as argon or a nitrogen oxide. The production of such atmospheric glow discharges should be possible with a minimal investment in capital equipment and without the requirement of a vacuum system.

Potential Features of Ball Lightning Industrial Plasmas

Because ball lightning is observed to occur at 1 atm and in atmospheric air, it seems a reasonable implication that steady-state glow discharges that are to be used for industrial plasma processing should also be possible at 1 atm and without the requirement of expensive vacuum systems. The relatively long lifetime and relatively low levels of energy dissipation associated with ball lightning observations imply that a 1-atm glow discharge based on ball lightning physics can be not only of a relatively small size but also of a relatively small power consumption. This is especially important by comparison with the vacuum systems required for low-pressure plasma processing. Not only are the vacuum systems a very expensive capital investment, but a great deal of power is needed to drive the required vacuum pumps to run such systems.

Potential Industrial Applications of Ball Lightning Plasmas

The production of a steady-state glow discharge at 1 atm of pressure would make possible under ambient conditions a number of industrial plasma processing operations that now must be carried out in vacuum systems. These processes include the antistatic surface treatment of plastic films; plasma chemical surface reactions in which active chemical species produced by the plasma will react with the surface to produce a desired effect; and plasma surface treatment to improve the wettability, dyeability, or printability of textiles and other fabrics. In addition, a 1-atm glow discharge plasma could provide synthetic or destructive plasma chemistry at 1 atm without the need to operate in a vacuum system. By using the proper heterogeneous surface chemical reactions, the deposition of thin films or their etching at 1 atm may also be possible.

Perhaps one of the most extensive and significant potential applications of atmospheric glow discharge plasmas might be the deposition and etching of microelectronic circuits at 1 atm rather than at low pressures in a vacuum system. Naturally, the approach would have to be substantially different than the deposition and etching techniques currently used at low pressures. For example, one would probably have to rely on heterogeneous surface chemical reactions to lay down thin films, and one would have to rely on the plasma-chemical equivalent of placer mining to etch patterns on surfaces under a mask. These atmospheric placer mining techniques would consist of blowing air or background gas laden with active species from the plasma downward on the mask and etching away the substrate by heterogeneous chemical reactions with the film.

SUMMARY

If the potential of ball lightning plasmas for military applications, fusion reactors, and industrial plasma processing is to be realized, a beginning needs to be made on the basic research and developmental work needed to provide the necessary information about ball lightning physics. One of the principal reasons that ball lightning is not better understood is that as a random natural event that cannot yet be duplicated in the laboratory, it is not accessible to scientific investigation, and it has not been possible, except in rare chance encounters, to apply scientific instruments to the measurement of its characteristics. Clearly, a major task is to reliably and reproducibly generate ball lightning in the laboratory. When this is done, ball lightning should be accessible to scientific investigation and to the application of modern plasma diagnostic methods. These methods should provide information that will either confirm, modify, or replace the Koloc and other previously discussed models.

Once information becomes available from the experimental investigation of laboratory-created ball lightning, then theoretical modeling of ball lightning can proceed. This modeling will probably proceed rapidly in view of the large body of knowledge already available in the fusion community relating to the Spheromak and other similar plasma containment configurations. This theoretical understanding should also allow one to generate ball lightning in the steady state and to determine scaling laws that relate ball lightning number densities, kinetic temperatures, and containment times so that some indication will become available concerning the region of plasma parameter space that ball lightning is capable of covering.

ACKNOWLEDGMENT

This paper was supported in part by the Air Force Office of Scientific Research under contracts AFOSR 89-0319 (Roth) and AFOSR F49620-94-10249.

REFERENCES

1. M. A. UMAN, *Lightning*, p. 243, McGraw Hill Book Company, New York (1969).

2. S. SINGER, *Lightning: Physics of Lightning*, Vol. 1, Chap. 12, p. 409, R. H. GOLDE, Ed., Academic Press, New York (1977).

3. S. SINGER, *The Nature of Ball Lightning*, Plenum Press, New York (1971).

4. J. D. BARRY, *Ball Lightning and Bead Lightning*, Plenum Press, New York (1980).

5. J. R. McNALLY, Jr., "Preliminary Report on Ball Lightning," ORNL 3938, Oak Ridge National Laboratory (May 1966).

6. W. D. RAYLE, "Ball Lightning Characteristics," NASA-TND-3188, National Aeronautics and Space Administration (Jan. 1966).

7. I. ALEXEFF and M. RADER, "Observation of Closed Loops in High Voltage Discharges: A Possible Precursor of Magnetic Flux Trapping," *IEEE Trans. Plasma Sci.*, **20**, *6*, 669 (1992).

8. Y. H. OHTSUKI and H. OFURUTON, "Plasma Fireballs Formed by Microwave Interference in Air," *Nature*, **350**, 139 (Mar. 1991).

9. Y. H. OHTSUKI and H. OFURUTON, "Nature of Ball Lightning in Japan," *Nuovo Cimento C*, **10**, *5*, 577 (1987).

10. J. R. ROTH, "Ball Lightning as a Route to Fusion Energy," *Proc. 13th Symp. Fusion Energy*, Knoxville, Tennessee, October 2–6, 1989, Vol. II, p. 1407 (1989).

11. E. WITALIS, "Ball Lightning as a Magnetized Air Plasma Whirl Structure," *J. Meteorol.*, **15**, 121 (1990).

12. J. R. ROTH, *Introduction to Fusion Energy*, Ibis Publishing, Charlottesville, Virginia (1986).

13. R. N. SUDAN, "High-Current Ion-Ring Accelerator," *Phys. Rev. Lett.*, **70**, *11*, 1623 (1993).

14. J. T. SLOUGH et al., "Confinement and Stability of Plasmas in a Field-Reversed Configuration," *Phys. Rev. Lett.*, **69**, *15*, 2212 (1992).

15. A. AL-KARKHY, P. K. BROWNING, G. CUNNINGHAM, S. J. GEE, and M. G. RUSBRIDGE, "Observations of the Magnetohydrodynamic Dynamo Effect in a Spheromak Plasma," *Phys. Rev. Lett.*, **70**, *12*, 1814 (1993).

16. E. A. WITALIS, "Hall Magnetohydrodynamics and Its Applications to Laboratory and Cosmic Plasma," *IEEE Trans. Plasma Sci.*, **PS-14**, *6*, 842 (1986).

17. P. M. KOLOC, "The Plasmak Configuration and Ball Lightning," *Proc. Int. Symp. Ball Lightning*, Tokyo, Japan, July 1988.

18. P. M. KOLOC, "Plasmak Star Power for Energy Intensive Space Applications," *Fusion Technol.*, **15**, 1136 (1989).

19. P. M. KOLOC, *Method and Apparatus for Generating and Utilizing a Compound Plasma Configuration*, U.S. Patent 4,023,065 (May 10, 1977).

20. R. GELLER and J. HOSEA, "Electron-Neutral Scattering Cross Sections," Report EUR-CEA-FC-459, Centre d'Etudes Nucleaires de Fontenay-aux-Roses (Mar. 1968).

J. Reece Roth (SB, physics, Massachusetts Institute of Technology, 1959; PhD, engineering physics, Cornell University, 1963) joined the National Aeronautics and Space Administration (NASA) Lewis Research Center in Cleveland, Ohio, in 1963, where he was principal investigator of the Lewis Electric Field Bumpy Torus Project until 1978. At present he is on the faculty of the electrical and computer engineering department of the University of Tennessee, Knoxville. While at NASA, Roth pioneered in the application of superconducting magnet facilities to high-temperature plasma research. This work included a superconducting magnetic mirror machine, which was put in service in 1964, and the superconducting Bumpy Torus magnet facility, which was put in service in 1972. Roth initiated research on the electric field Bumpy Torus concept, an approach to creating a plasma of fusion interest in which strong radial electric fields are imposed on a Bumpy Torus plasma in such a way that they contribute to the heating, stability, and confinement of the plasma. Among his contributions to the understanding of basic processes in plasmas are his experimental discovery of the continuity-equation oscillation and of the geometric mean plasma frequency, a new mode of electromagnetic emission from plasmas.

APPENDIX F

Invited Seminar

BRIEFING NOTICE

A NEW ATMOSPHERIC GLOW DISCHARGE FOR FLUID MECHANICAL CONTROL USING A PLASMA SURFACE LAYER

Prof. J. Reece Roth
UTK Plasma Sciences Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, TN 37996-2100
(615)974-4446

Friday, February 24, 1995
Building 1247A, Room 310
2:00-3:00 PM

ABSTRACT

At the University of Tennessee's Plasma Science Laboratory, we have recently developed, with AFOSR support, a new type of uniform glow discharge plasma in a parallel plate geometry, which is capable of operating at one atmosphere in air and other gases. This plasma is neither a corona discharge nor a filamentary (ozonizer) discharge, the more familiar electrical discharges which are also capable of operating at one atmosphere. The physical processes which make this discharge possible are based on a RF ion trapping mechanism and will be described theoretically. The RF frequency, electric field, and electrode separation required to maintain this discharge will be derived from first principles. Characteristic operating and plasma parameters in air at one atmosphere are: RF frequency, 1-6 kHz; RMS electric field ~9kV/cm; maximum RMS voltage= 4kV; plasma number density = 10^{10} electrons/cm^3; and the input power density 10-200 milliwatts/cm^3. The maximum volume of uniform plasma generated to date has been 2.8 liters between parallel plates.

More recently, the parallel plate geometry described above has been geometrically transformed and made to operate on a planar surface, producing a steady-state plasma layer up to several millimeters thick. The electric field in this surface plasma layer can provide a body force per unit area of up to perhaps several thousand pascals. Some speculative applications to boundary layer control, turbulence suppression, drag reduction and noise reduction will be put forward.

Briefing Coordinator: Steve Wilkinson, 45733

BOUNDARY LAYER CONTROL BY A ONE ATMOSPHERE UNIFORM GLOW DISCHARGE PLASMA LAYER

Prof. J. Reece Roth
UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, TN 37996-2100
(615) 974-4446

ABSTRACT

At the University of Tennessee's Plasma Science Laboratory, we have recently developed, with AFOSR support, a new type of uniform glow discharge plasma in a parallel plate geometry, which is capable of operating at one atmosphere in air and other gases. This plasma is neither a corona discharge nor a filamentary (ozonizer) discharge, the more familiar electrical discharges which are also capable of operating at one atmosphere. The physical processes which make this discharge possible are based on an RF ion trapping mechanism, and will be described theoretically. The RF frequency, electric field, and electrode separation required to maintain this discharge will be derived from first principles. Characteristic operating and plasma parameters in air at one atmosphere are: RF frequency, 1-6 kHz; RMS electric field ≈ 9 kV/cm; maximum RMS voltage ≈ 4 kV; plasma number density ≈ 10^{10} electrons/cm^3; and input power density 10-200 milliwatts/cm^3. The maximum volume of uniform plasma generated to date has been 2.8 liters between parallel plates.

More recently, the parallel plate geometry described above has been geometrically transformed and made to operate on a planar surface, producing a steady-state plasma layer up to several millimeters thick. The electric field in this surface plasma layer can provide a body force per unit area of up to perhaps several thousand pascals. Some speculative applications to boundary layer control, turbulence suppression, drag reduction, and noise reduction will be put forward. Offers of support for our research program at the UTK Plasma Science Laboratory, or of research collaboration from individuals or groups with access to a wind tunnel, will be particularly welcome.

Prepared for presentation at the Kirtland Air Force Base, Albuquerque, NM, Monday, March 6, 1995.